US 20240235682A1

(19) **United States**

(12) **Patent Application Publication** (10) **Pub. No.: US 2024/0235682 A1**

BIGONGIARI et al. (43) **Pub. Date: Jul. 11, 2024**

(54) **PHOTONIC RF SIGNAL GENERATION APPARATUS, NETWORK UNITS AND METHOD**

(71) Applicant: **Telefonaktiebolaget LM Ericsson (publ)**, Stockholm (SE)

(72) Inventors: **Alessandra BIGONGIARI**, Pisa (IT); **Antonio D'ERRICO**, Pisa (IT); **Antonio MALACARNE**, Pisa (IT); **Marco SECONDINI**, Pisa (IT); **Claudio PORZI**, Pisa (IT)

(21) Appl. No.: **18/562,036**

(22) PCT Filed: **May 11, 2022**

(86) PCT No.: **PCT/EP2022/062857**

§ 371 (c)(1),
(2) Date: **Nov. 17, 2023**

(30) **Foreign Application Priority Data**

May 19, 2021 (WO) PCT/EP2021/063285

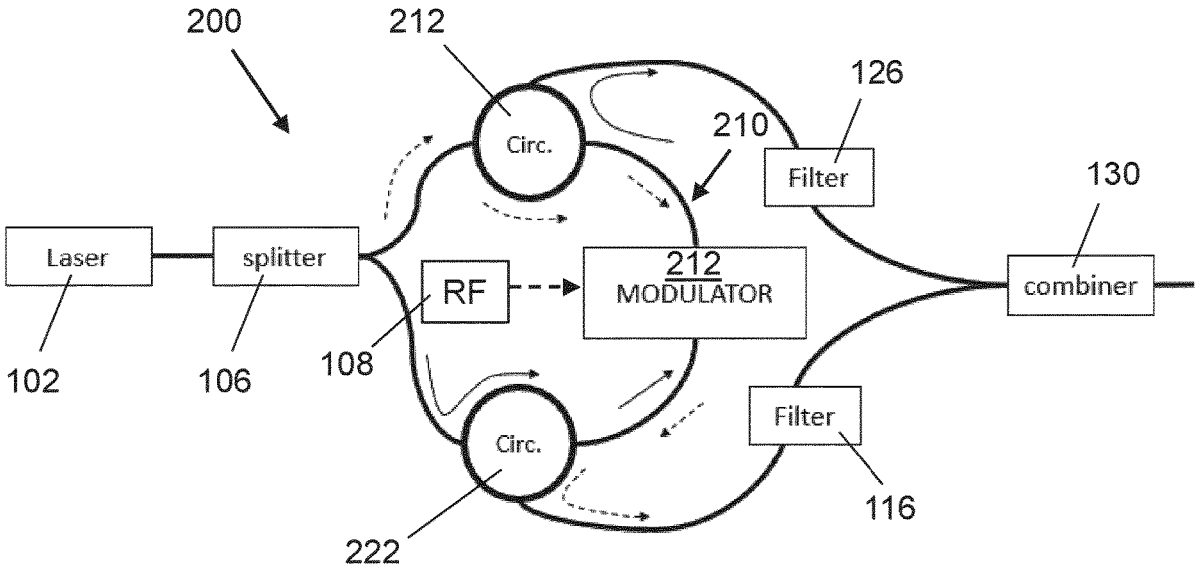
Publication Classification

(51) **Int. Cl.**
H04B 10/2575 (2006.01)
H04B 10/50 (2006.01)

(52) **U.S. Cl.**
CPC ***H04B 10/2575*** (2013.01); ***H04B 10/50*** (2013.01)

(57) **ABSTRACT**

A photonic radio frequency, RF, signal generation apparatus has a source to output a coherent optical signal at a carrier frequency; an optical splitter to split the signal into a first and a second optical carrier signal; an RF signal generation apparatus generating an RF signal at an initial frequency; an optical modulation apparatus modulating the first and second signals at the initial frequency to generate optical harmonic signals around each signal; a first optical filter to select an nth order optical harmonic signal of a first sign, +n, of the optical harmonics around the first signal; a second optical filter to select the nth order optical harmonic signal of an opposite sign, −n, of the optical harmonics around the second signal; and a combiner to combine the selected +n and −n signals to generate an optical beat signal forming an output photonic RF signal.



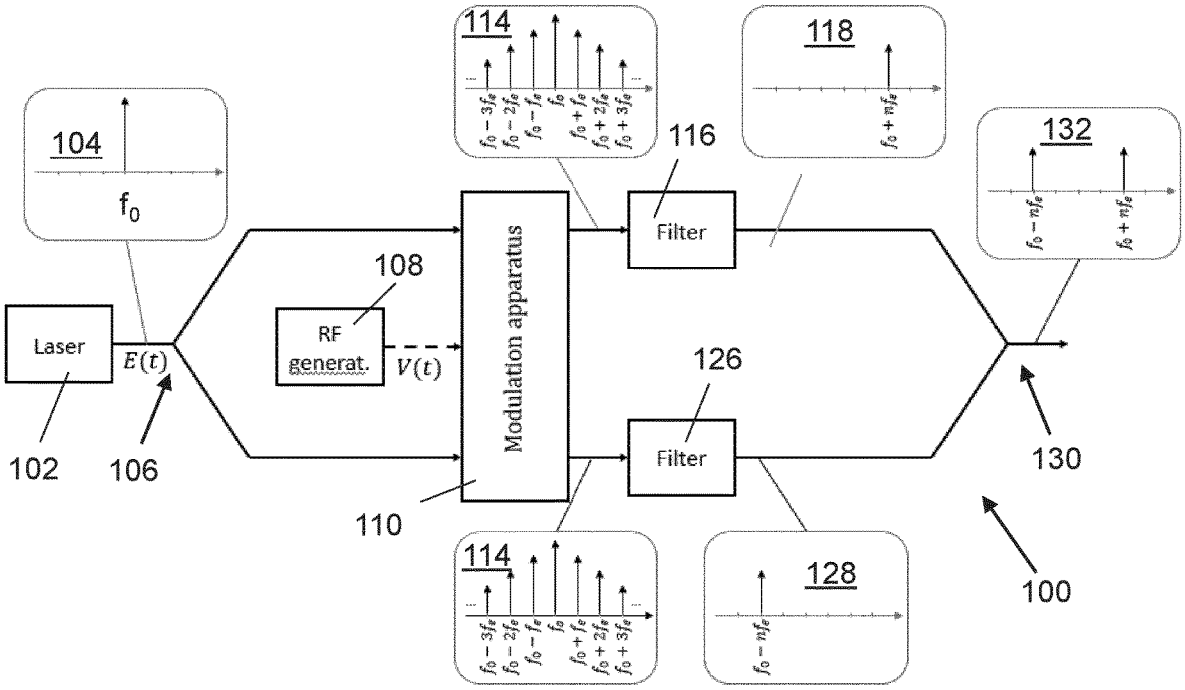

114
118
104
f_0
116
132
Filter
108
Laser
RF generat.
$E(t)$
$V(t)$
Modulation apparatus
126
Filter
102
106
110
130
114
128
100

Fig. 1a

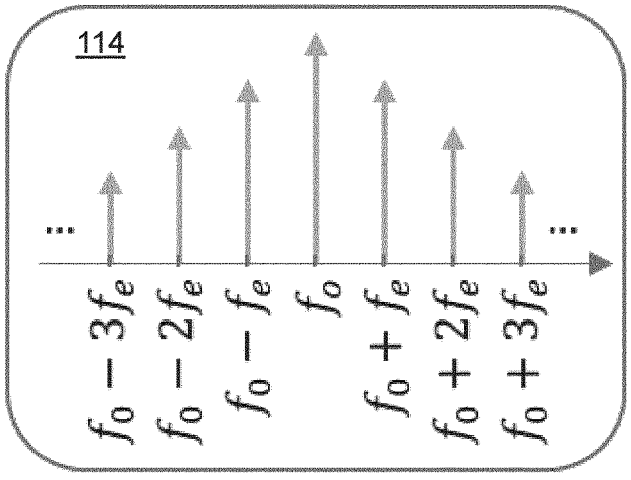

114
$f_0 - 3f_e$
$f_0 - 2f_e$
$f_0 - f_e$
f_0
$f_0 + f_e$
$f_0 + 2f_e$
$f_0 + 3f_e$

Fig. 1b

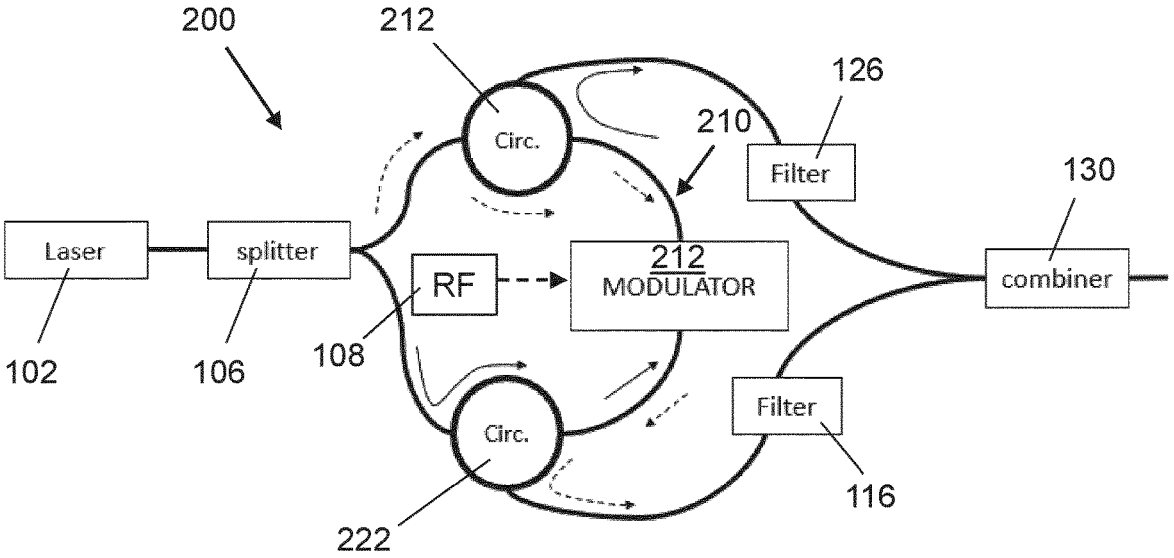

200
212
126
Circ.
210
Filter
130
Laser
splitter
RF
212
MODULATOR
combiner
102
106
108
Filter
Circ.
116
222

Fig. 2

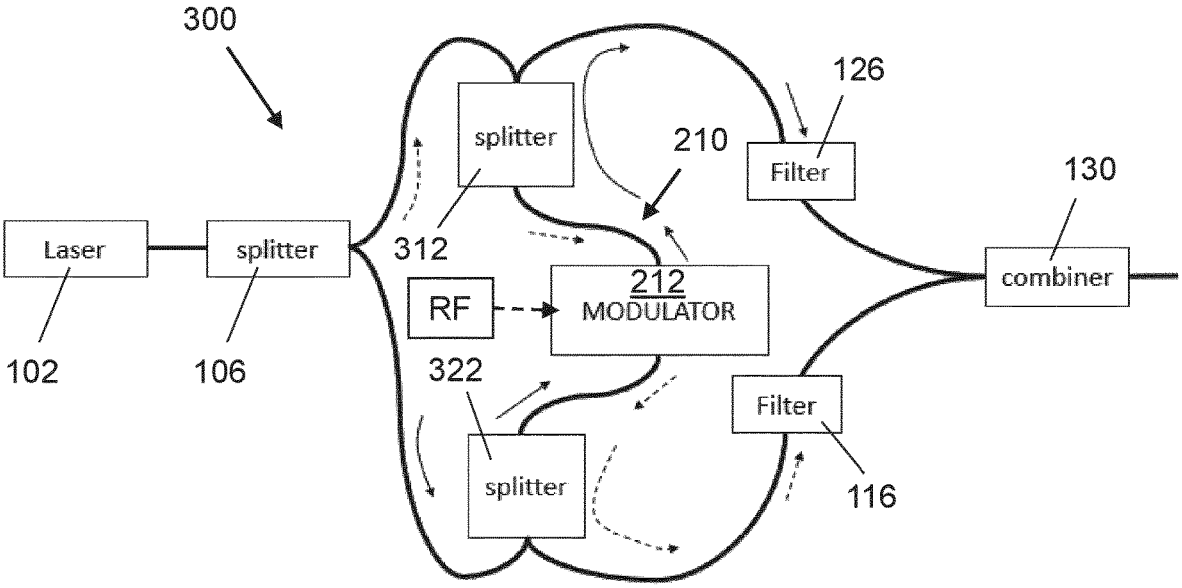

300
126
splitter
210
Filter
130
Laser
splitter
312
RF
212
MODULATOR
combiner
102
106
322
Filter
splitter
116

Fig. 3

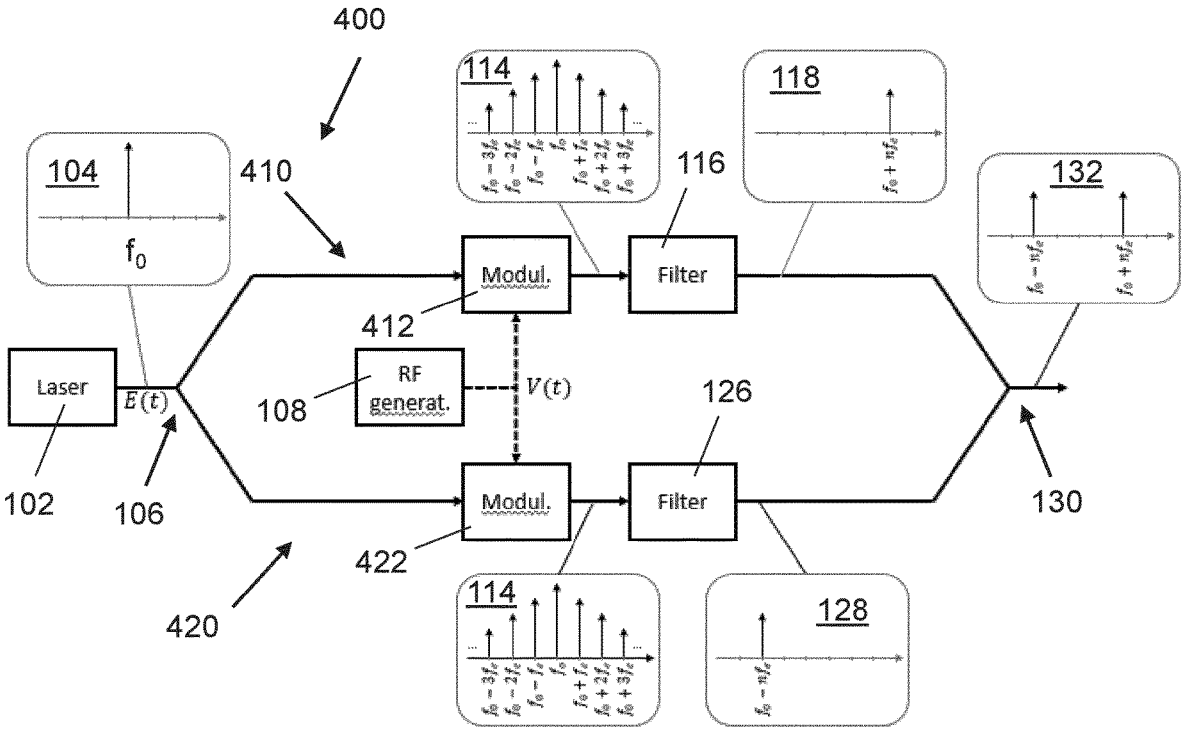

400
104
f_0
410
114
116
118
132
Modul.
Filter
412
Laser
$E(t)$
108
RF generat.
$V(t)$
126
102
106
Modul.
Filter
130
422
420
114
128

Fig. 4

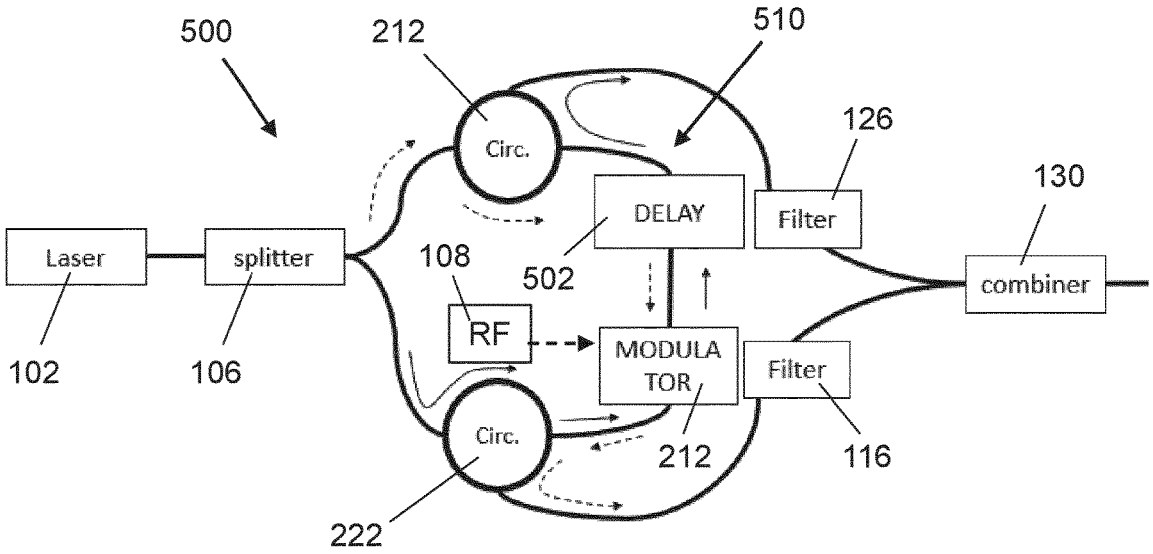

500
212
510
126
130
Circ.
DELAY
Filter
Laser
splitter
108
502
combiner
RF
MODULA
TOR
Filter
102
106
Circ.
212
116
222

Fig. 5

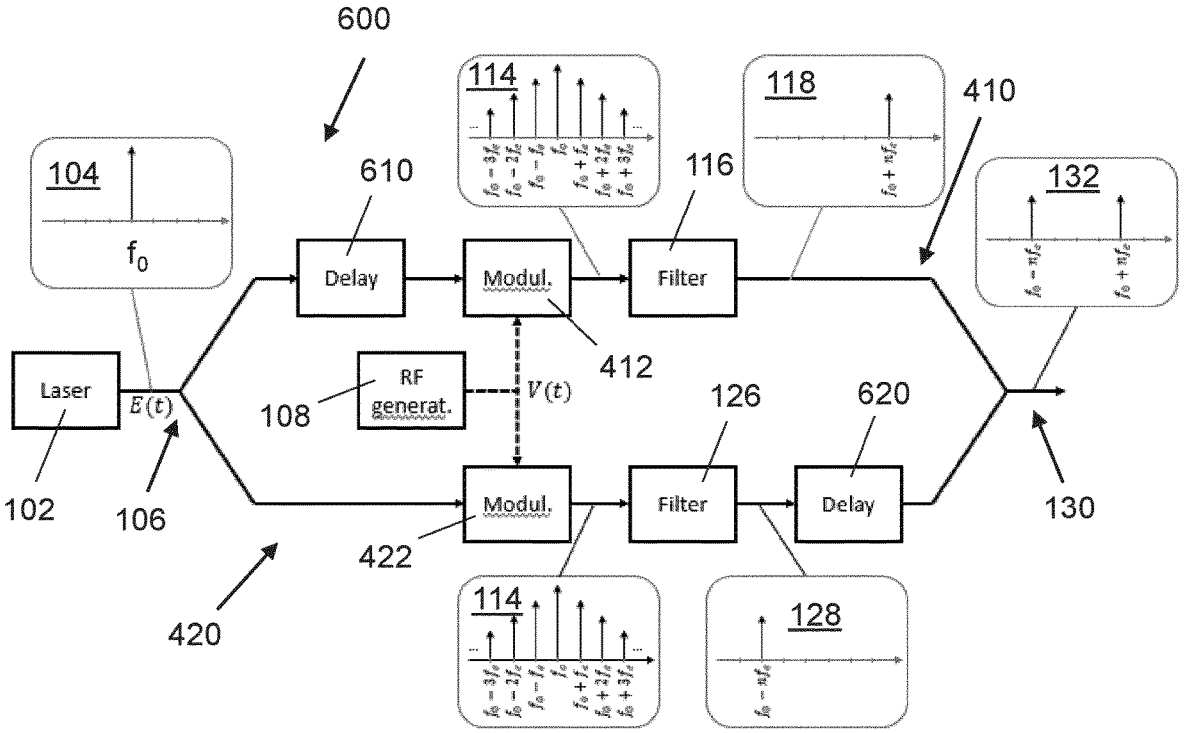

600
114
118
410
104
610
116
132
f_0
Delay
Modul.
Filter
412
Laser
$E(t)$
108
RF
generat.
$V(t)$
126
620
102
106
Modul.
Filter
Delay
130
422
420
114
128

Fig. 6

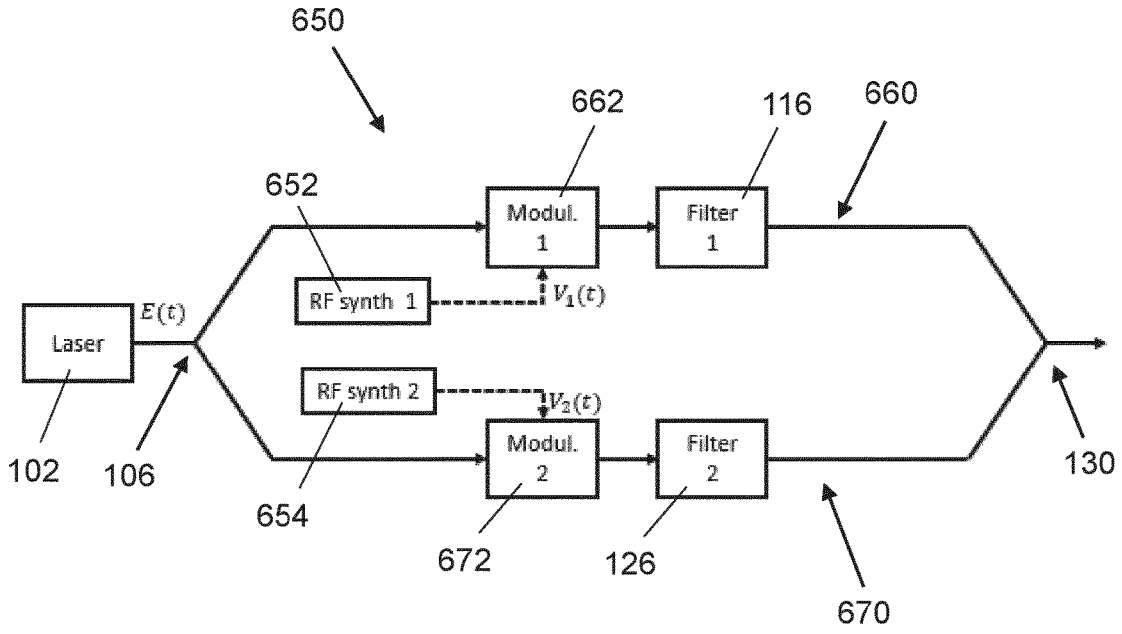

650
662
116
660
652
Modul. 1
Filter 1
RF synth 1
$V_1(t)$
$E(t)$
Laser
RF synth 2
$V_2(t)$
Modul. 2
Filter 2
102
106
654
672
126
130
670

Fig. 7

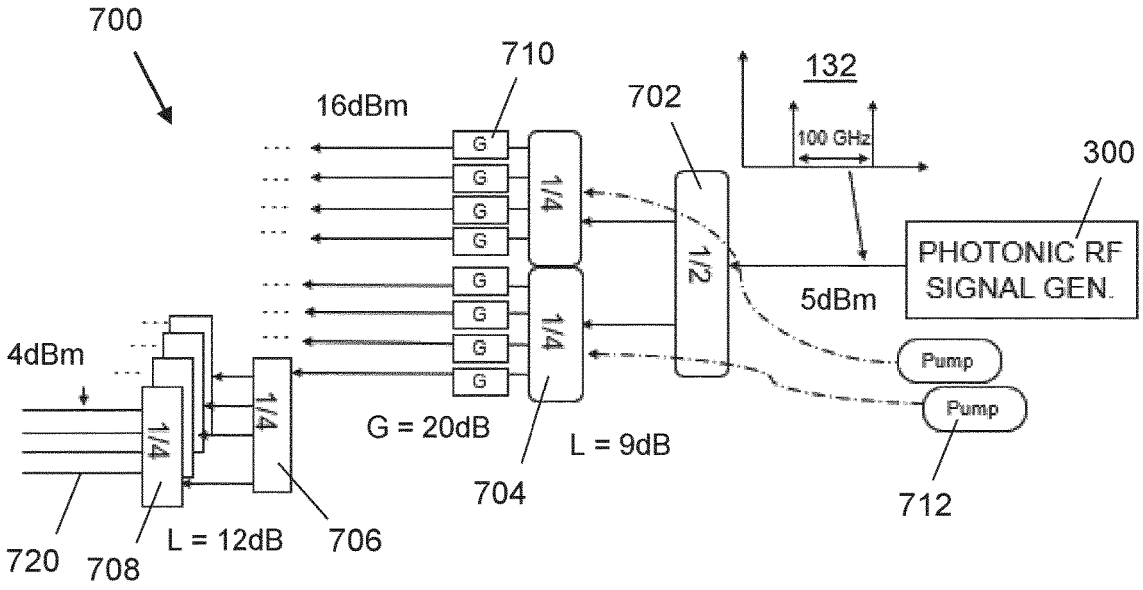

700
710
16dBm
132
702
100 GHz
300
G
1/4
1/2
PHOTONIC RF SIGNAL GEN.
5dBm
Pump
Pump
4dBm
G = 20dB
L = 9dB
704
712
720
708
L = 12dB
706

Fig. 8

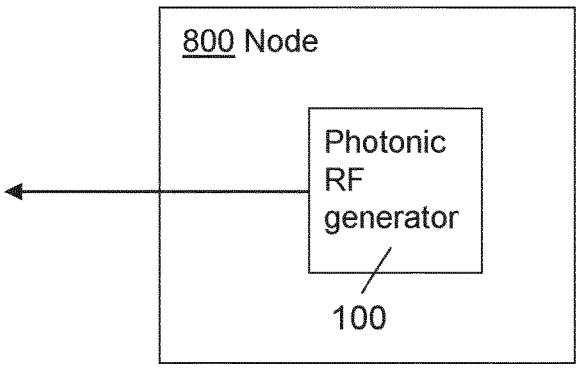

800 Node
Photonic RF generator
100

Fig. 9

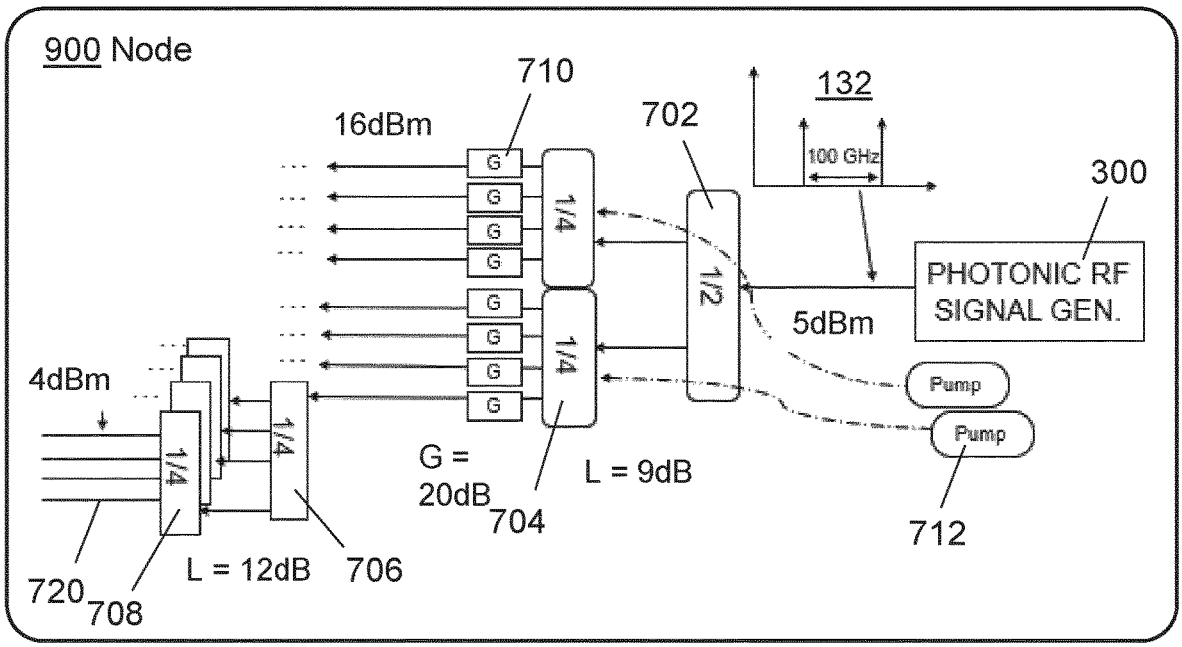

900 Node
710
16dBm
702
132
100 GHz
300
PHOTONIC RF SIGNAL GEN.
5dBm
G
1/4
1/2
Pump
Pump
4dBm
G = 20dB
L = 9dB
704
712
720
708
L = 12dB
706

Fig. 10

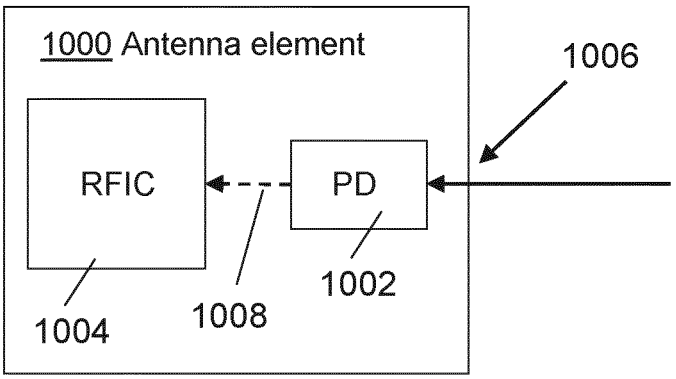

1000 Antenna element
1006
RFIC
PD
1002
1004
1008

Fig. 11

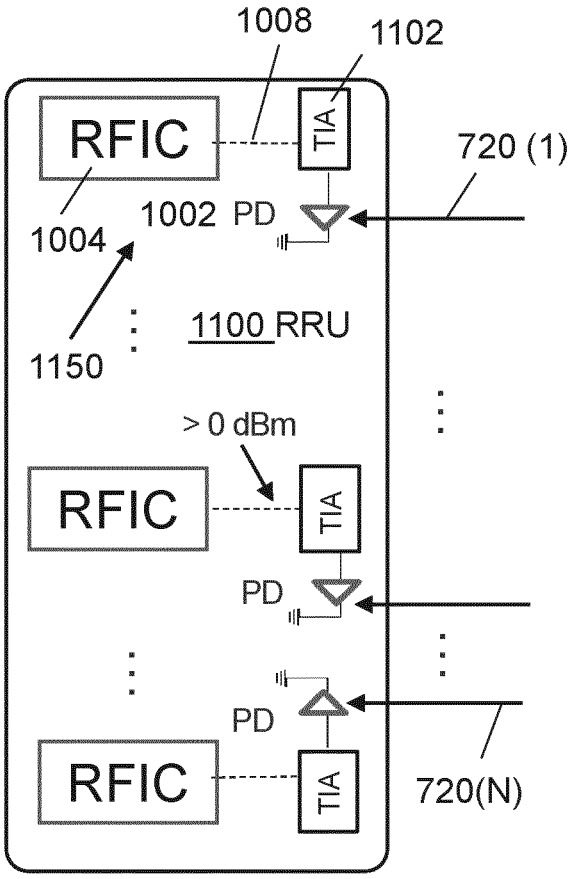

1008
1102
RFIC
TIA
720 (1)
1004
1002
PD
1150
1100 RRU
> 0 dBm
RFIC
TIA
PD
PD
RFIC
TIA
720(N)

Fig. 12

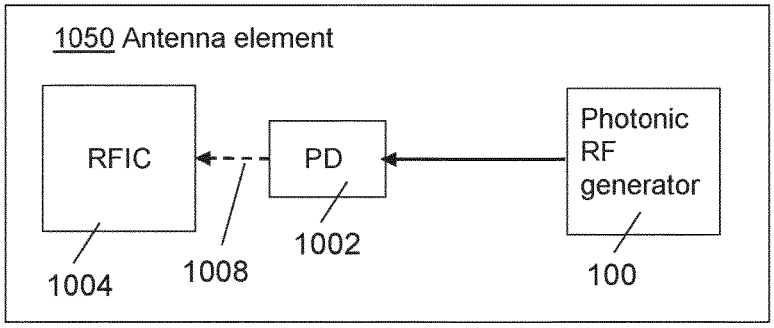


Fig. 11A

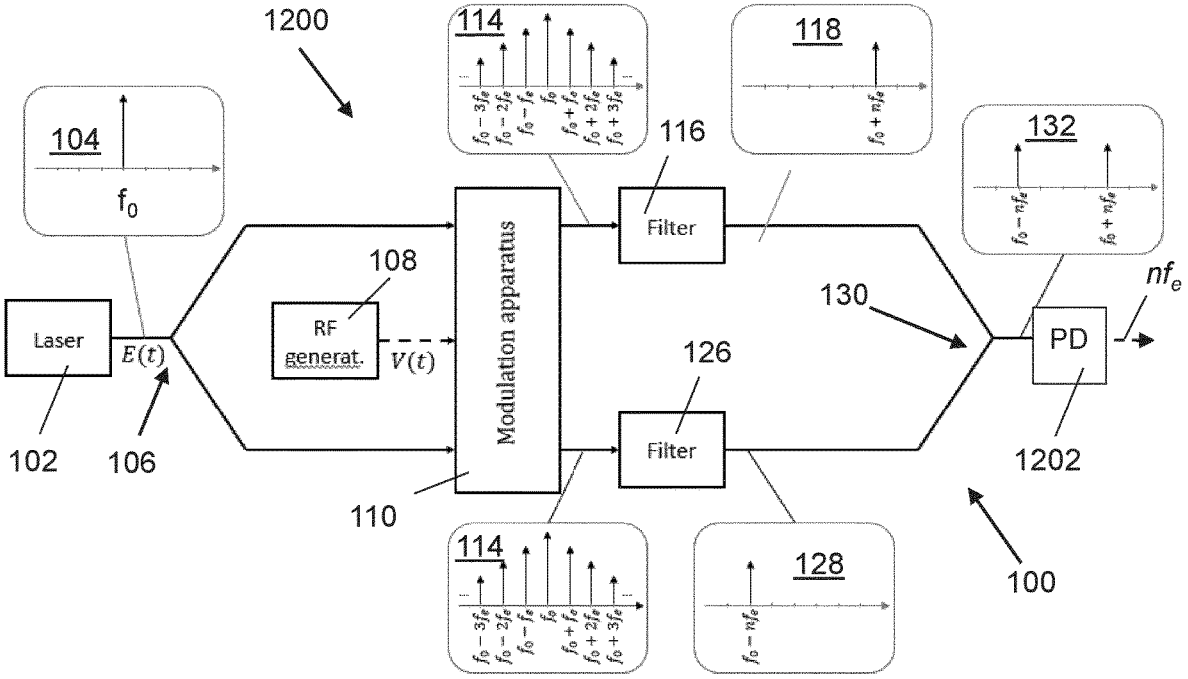


Fig. 13

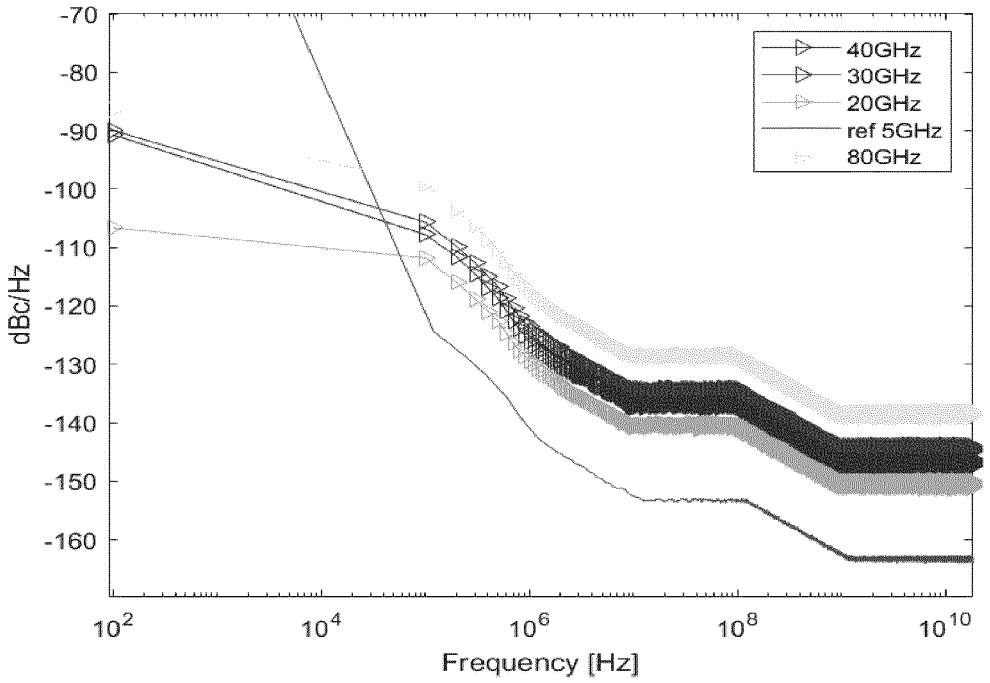

-70
-80
-90
-100
-110
-120
-130
-140
-150
-160
dBc/Hz
10^2
10^4
10^6
10^8
10^{10}
Frequency [Hz]
40GHz
30GHz
20GHz
ref 5GHz
80GHz

Fig. 14

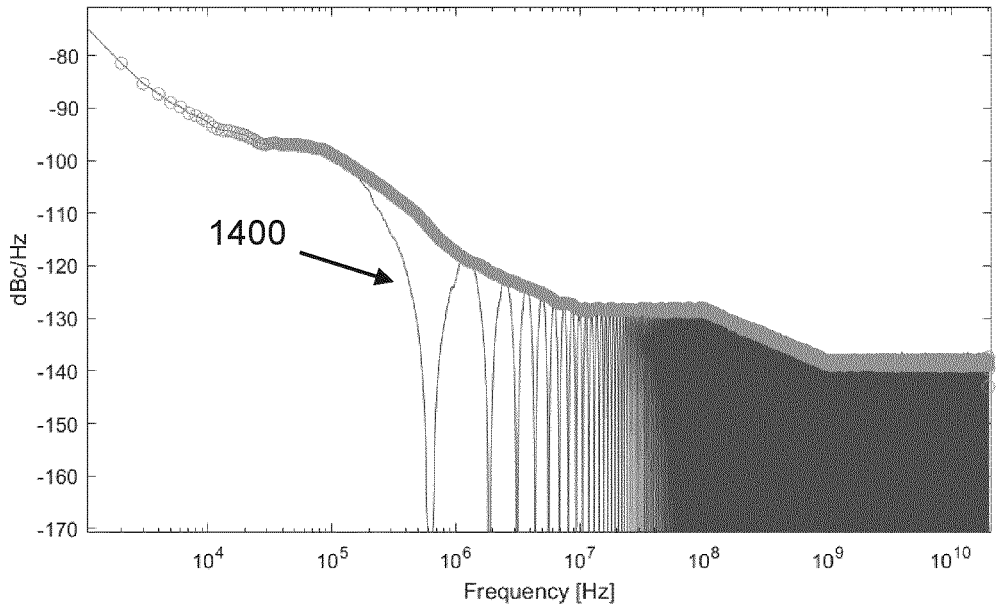

-80
-90
-100
-110
-120
-130
-140
-150
-160
-170
dBc/Hz
1400
10^4
10^5
10^6
10^7
10^8
10^9
10^{10}
Frequency [Hz]

Fig. 15

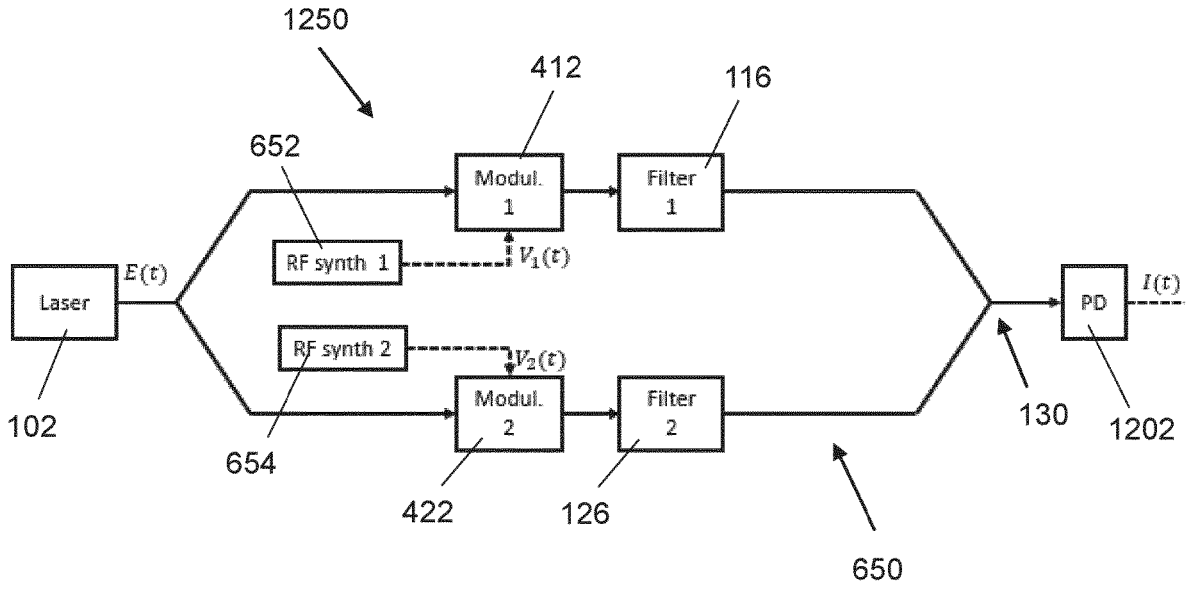

1250
412
116
652
Modul. 1
Filter 1
RF synth 1
$V_1(t)$
Laser
$E(t)$
PD
$I(t)$
RF synth 2
$V_2(t)$
Modul. 2
Filter 2
102
654
422
126
130
1202
650

Fig. 16

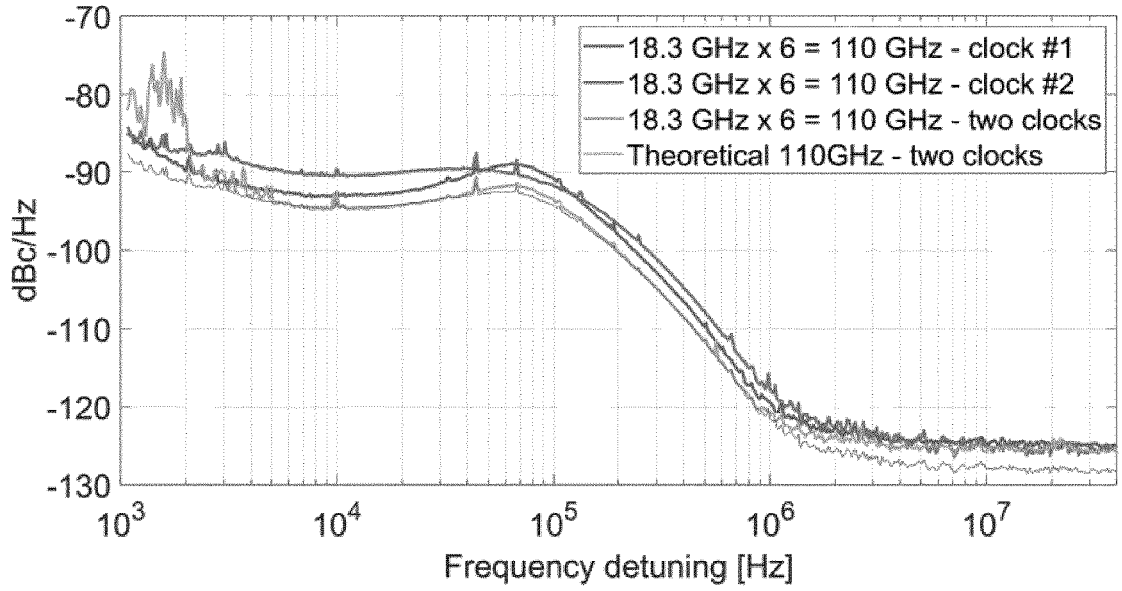

18.3 GHz x 6 = 110 GHz - clock #1
18.3 GHz x 6 = 110 GHz - clock #2
18.3 GHz x 6 = 110 GHz - two clocks
Theoretical 110GHz - two clocks
dBc/Hz
-70
-80
-90
-100
-110
-120
-130
10^3
10^4
10^5
10^6
10^7
Frequency detuning [Hz]

Fig. 17

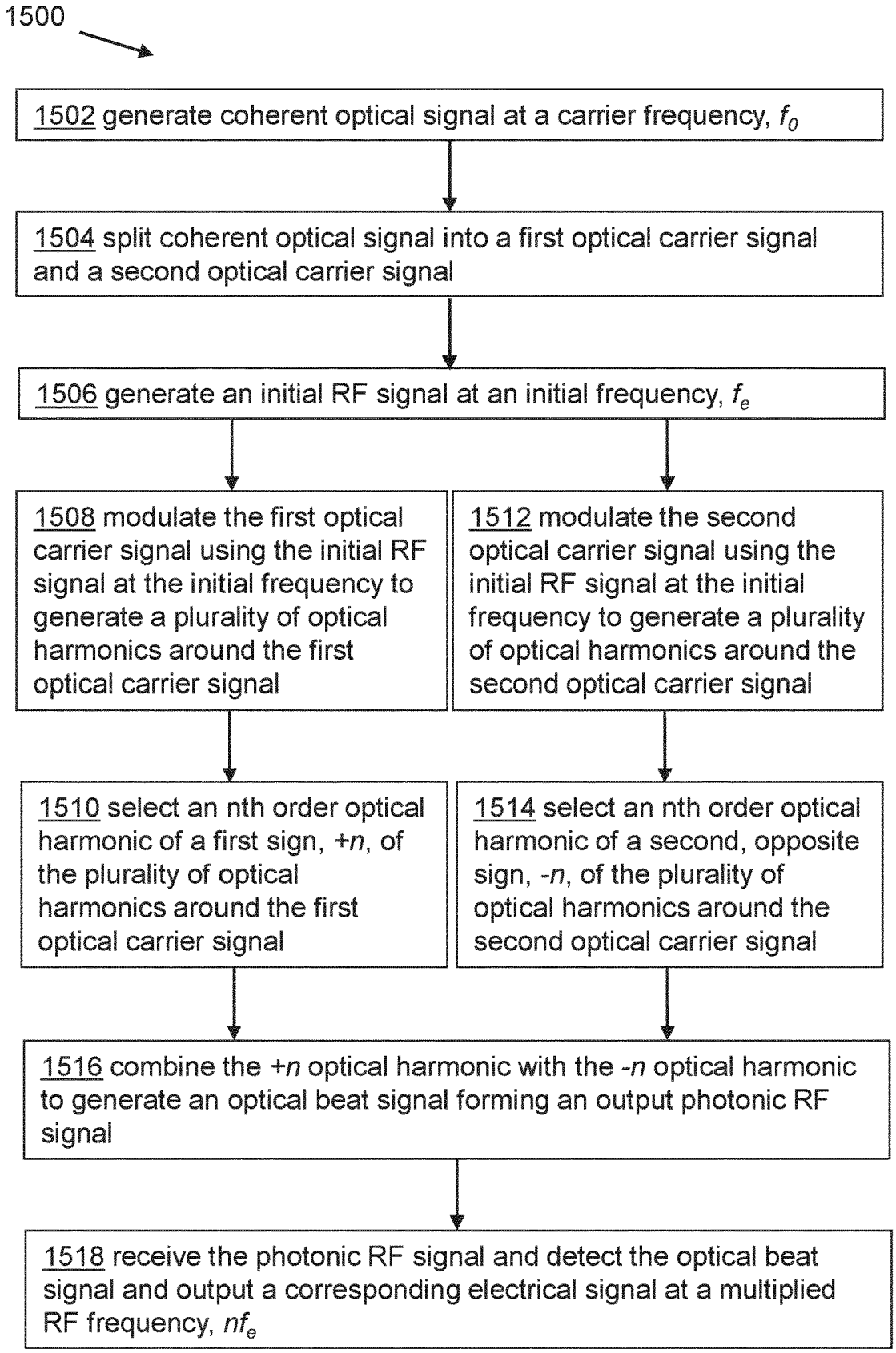

1500
1502 generate coherent optical signal at a carrier frequency, f_0
1504 split coherent optical signal into a first optical carrier signal and a second optical carrier signal
1506 generate an initial RF signal at an initial frequency, f_e
1508 modulate the first optical carrier signal using the initial RF signal at the initial frequency to generate a plurality of optical harmonics around the first optical carrier signal
1512 modulate the second optical carrier signal using the initial RF signal at the initial frequency to generate a plurality of optical harmonics around the second optical carrier signal
1510 select an nth order optical harmonic of a first sign, +n, of the plurality of optical harmonics around the first optical carrier signal
1514 select an nth order optical harmonic of a second, opposite sign, -n, of the plurality of optical harmonics around the second optical carrier signal
1516 combine the +n optical harmonic with the -n optical harmonic to generate an optical beat signal forming an output photonic RF signal
1518 receive the photonic RF signal and detect the optical beat signal and output a corresponding electrical signal at a multiplied RF frequency, nf_e

Fig. 18

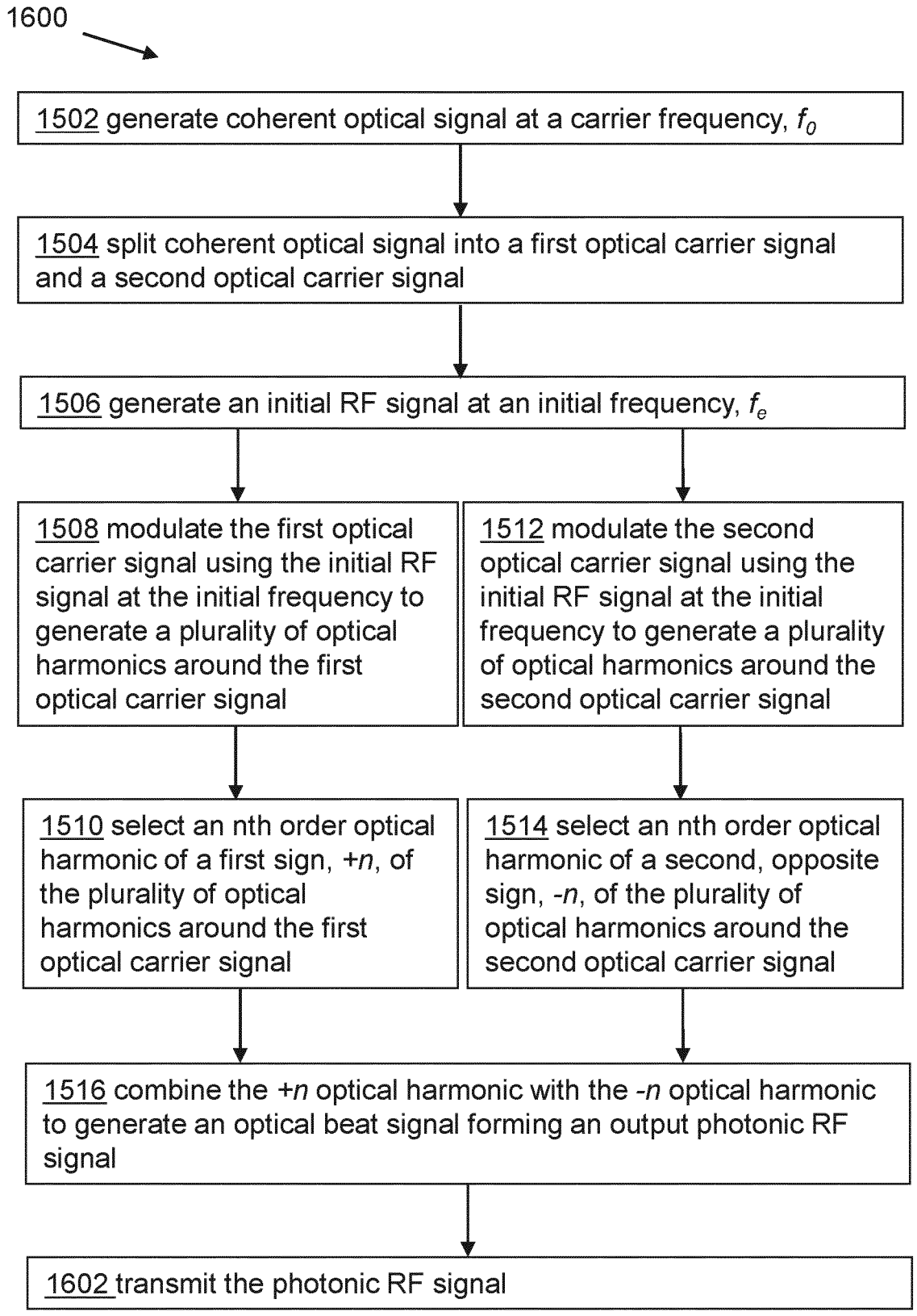

1600
1502 generate coherent optical signal at a carrier frequency, f_0
1504 split coherent optical signal into a first optical carrier signal and a second optical carrier signal
1506 generate an initial RF signal at an initial frequency, f_e
1508 modulate the first optical carrier signal using the initial RF signal at the initial frequency to generate a plurality of optical harmonics around the first optical carrier signal
1512 modulate the second optical carrier signal using the initial RF signal at the initial frequency to generate a plurality of optical harmonics around the second optical carrier signal
1510 select an nth order optical harmonic of a first sign, +n, of the plurality of optical harmonics around the first optical carrier signal
1514 select an nth order optical harmonic of a second, opposite sign, -n, of the plurality of optical harmonics around the second optical carrier signal
1516 combine the +n optical harmonic with the -n optical harmonic to generate an optical beat signal forming an output photonic RF signal
1602 transmit the photonic RF signal

Fig. 19

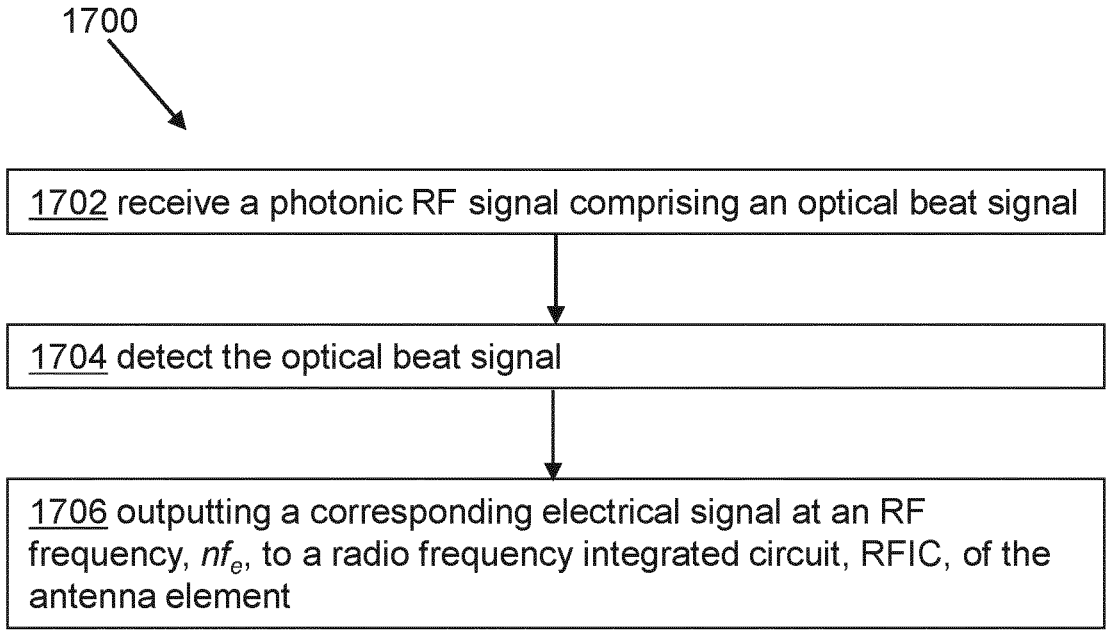

1700
1702 receive a photonic RF signal comprising an optical beat signal
1704 detect the optical beat signal
1706 outputting a corresponding electrical signal at an RF frequency, nf_e, to a radio frequency integrated circuit, RFIC, of the antenna element

Fig. 20

PHOTONIC RF SIGNAL GENERATION APPARATUS, NETWORK UNITS AND METHOD

TECHNICAL FIELD

[0001] The invention relates to photonic radio frequency, RF, signal generation apparatus and to a communications network node comprising the photonic RF signal generation apparatus. The invention further relates to a communications network antenna element. The invention further relates to RF signal multiplication apparatus. The invention further relates to a method of generating a multiplied RF signal, a method of generating a photonic RF signal and a method at a communications network antenna element.

BACKGROUND

[0002] At present, deployed mid-band radios operate on a frequency band that is around 3.5 Ghz or 6 GHz. New Radio hardware, in 5G deployment and beyond, will be transmitting at a higher frequency, in the Extremely High-Frequency range (30-300 GHz), also known as the mmW domain.

[0003] Devices operating at high frequency need to generate a reference clock at the operating frequency. This reference clock is commonly obtained from a reference at a lower frequency that is upconverted in an electrical multiplier. This enables a low-frequency reference to be transmitted on electrical lines without losses and signal integrity problems.

[0004] Current solutions for the generation of a high-frequency RF carrier signals are commonly based on the use of synthesizers which produce the desired frequency by multiplying a reference frequency from a local oscillator, in a Phase-Locked Loop, PLL, circuit. The PLL comprises a phase detector that returns a signal proportional to the phase difference of the input reference frequency fin and the output frequency four. A loop filter is coupled to the output of the phase detector and is a low pass filter that reduces jitter in noisy inputs and selects the desired phase difference. The output of the loop filter is a voltage which is used to control a voltage controlled oscillator, VCO, so that is generates an oscillating electrical signal. The VCO is forced to settle on a value that matches the long-term average of the input frequency. The value of "long term average" is determined by the characteristics of the loop components, including the low-pass filter. The reference frequency is generally a crystal with high spectral purity that is multiplied several times. However, the multiplication steps tend to increase inherent phase noise of the reference and add further noise sources. This results in the production of relevant phase noise in high-frequency clock signals obtained through several PLL multiplication stages.

[0005] Phase noise generation is one of the most detrimental effects for radio performance since it determines effects such as Common Phase Error, CPE, due to constellation rotation of an orthogonal frequency division multiplexing, OFDM, signal, and Inter-carrier Interference, ICI. Phase noise increases with RF carrier frequency, due to higher multiplication factors required in the PLL and generally lower performance of electronics in the high-frequency range. At present the countermeasure taken to handle phase noise for high carrier frequencies consists of increasing the spacing between OFDM subcarriers. In 5G the subcarrier spacing is flexible and can range from 15 to 240 KHz; large OFDM subcarrier spacing corresponds to higher RF carrier frequencies.

[0006] Current solutions based on frequency multiplication may be very efficient. However, the frequency multiplication process causes multiplication of any phase noise in the reference frequency, resulting in a high-frequency signal with significant phase noise. Ideally, for a pure multiplication of the reference frequency, the final phase noise can be derived from the phase noise, PN, of the reference frequency, PN_{ref}, using the following:

$$PN = PN_{ref} + 20^{*}\log(N)\ dBc/\text{Hz} \quad (1)$$

where N is the multiplication factor. It is desirable to have N as low as possible, to minimise multiplication of phase noise in the reference frequency. However, this option is limited by the availability of oscillators able to generate high enough reference frequencies, together with their cost and power consumption. Commonly, crystal oscillators are employed, generating a reference frequency of around 40-100 MHZ, with low power consumption. Crystals providing higher reference frequencies exist, but there is no proof this would improve the phase noise of the output high frequency signal.

[0007] High-frequency synthesiser solutions incur an unavoidable increase of phase noise when delivering a carrier frequency in the high-frequency range. A countermeasure might be to increase the subcarrier spacing to reduce ICI, but this would limit the utilization of the available bandwidth. One of the reasons why future radio deployments target high carrier frequencies is to deliver a larger capacity due to the larger bandwidth. If subcarrier spacing increases, the bandwidth increase brought by the high-frequency range may be significantly decreased.

[0008] US 2019/0004341 describes an opto-electronic oscillator comprising: an optical source to generate an optical carrier signal having a carrier wavelength; an optical phase modulator to apply a sinusoidal phase modulation to the optical carrier signal to generate two first order sidebands having a π phase difference between them; an optical phase shifter comprising an optical resonator configured to apply a substantially π phase-shift to one of the first order sidebands at a preselected wavelength within an optical spectrum of said first order sideband; and a photodetector configured to perform optical heterodyne detection of the optical carrier signal with both: said one of the first order sidebands substantially π phase shifted by the optical resonator; and the other of the first order sidebands, to generate an electrical carrier signal. A first part of the electrical carrier signal is delivered to an electrical output and a second part of the electrical carrier signal is delivered to the optical phase modulator as a drive signal. The oscillator enables an RF carrier to be produced that has very low phase noise with respect to a state of art electrical frequency multiplier, thanks to the feedback mechanism where the signal detected at the output of the optical oscillator is used in the modulator driver.

SUMMARY

[0009] It is an object to provide an improved Photonic radio frequency, RF, signal generation apparatus. It is a

further object to provide an improved communications network node. It is a further object to provide an improved communications network antenna element. It is a further object to provide an improved RF signal multiplication apparatus. It is a further object to provide an improved method of generating a multiplied RF signal. It is a further object to provide an improved method of generating a photonic RF signal. It is a further object to provide an improved method at a communications network antenna element.

[0010] An aspect of the invention provides photonic radio frequency, RF, signal generation apparatus comprising a coherent optical source, an optical splitter, RF signal generation apparatus, optical modulation apparatus, a first optical filter, a second optical filter and an optical combiner. The coherent optical source is operable to output a coherent optical signal at a carrier frequency, f_0. The optical splitter is arranged to split the coherent optical signal into a first optical carrier signal and a second optical carrier signal. The RF signal generation apparatus is operable to generate at least one RF signal (V(t)) at an initial frequency, f_e. The optical modulation apparatus is driven by the at least one RF signal and is operable to modulate the first optical carrier signal and the second optical carrier signal at the initial frequency to generate a plurality of optical harmonic signals around each optical carrier signal. The first optical filter is configured to select an nth order optical harmonic signal of a first sign, +n, of the plurality of optical harmonics around the first optical carrier signal. The second optical filter configured to select the nth order optical harmonic signal of an opposite sign, −n, of the plurality of optical harmonics around the second optical carrier signal. The optical combiner is arranged to combine the selected +n optical harmonic signal with the selected −n optical harmonic signal to generate an optical beat signal forming an output photonic RF signal.

[0011] The apparatus enables generation of a photonic RF signal in which optical phase noise is reduced or cancelled and phase noise introduced by the optical modulation apparatus is a pure multiple of the phase noise of the RF signal at the initial frequency. The apparatus thus advantageously enables the total phase noise of a photonic RF signal to be reduced as compared to the prior art, without requiring any modulation drive signal feedback mechanism. The apparatus may advantageously produce a high-frequency photonic RF signal from the multiplication of a low frequency oscillator or synthesizer, without adding any extra optical noise.

[0012] In an embodiment, the RF signal generation apparatus comprises an RF signal generator operable to generate an RF signal (V(t)) at the initial frequency, f_e.

[0013] In an embodiment, the optical modulation apparatus comprises a bi-directional optical modulator. The apparatus further comprises a first optical path from the optical splitter to the optical combiner for the first optical carrier signal and a second optical path from the optical splitter to the optical combiner for the second optical carrier signal. The first optical path includes: a path section including the bi-directional optical modulator operable to modulate the first optical carrier signal propagating in a first direction; and the first optical filter. The second optical path includes: the path section including the bi-directional optical modulator further operable to modulate the second optical carrier signal propagating in a second, opposite direction; and the second optical filter.

[0014] In an embodiment, the optical modulation apparatus comprises a first optical modulator operable to modulate the first optical carrier signal and a second optical modulator operable to modulate the second optical carrier signal. The apparatus further comprises a first optical path from the optical splitter to the optical combiner for the first optical carrier signal and a second optical path from the optical splitter to the optical combiner for the second optical carrier signal. The first optical path includes the first optical modulator and the first optical filter. The second optical path includes the second optical modulator and the second optical filter.

[0015] In an embodiment, the apparatus further comprises optical delay apparatus arranged to apply a delay, τ, to optical signals, the optical delay apparatus being arranged to apply the delay to the first optical carrier signal and to apply the delay to at least the −n optical harmonic signal.

[0016] The optical delay apparatus enables the apparatus to reduce or cancel phase noise introduced by the RF signal at the initial frequency that drives the optical modulation apparatus, i.e. the phase noise inherited from the RF signal, that is multiplied by twice the harmonic order, is reduced or cancelled. The apparatus may thereby generate a photonic RF signal in which both optical phase noise and electrical phase noise are reduced or cancelled. The apparatus may advantageously reduce the total phase noise of the photonic RF signal as compared to the prior art. The apparatus advantageously enables a high-frequency photonic RF signal to be produced from the multiplication of a low frequency RF signal generator, such as an oscillator or synthesizer, without adding any extra optical noise and reducing or cancelling the noise inherited from the RF signal generator.

[0017] The introduced delay may advantageously produce deep notches in the phase noise profile of the photonic RF signal at frequencies, f_m, (where f_m is the distance from the carrier frequency, f_0), that substantially cancel the noise locally and produce an overall decrease of the phase noise. The location of the notches can be selected by selecting the value of the delay t; the notches are located at the zeros of the function $\cos^2(\tau\pi f_m)$. For an orthogonal frequency division multiplexing, OFDM, transmission scheme, the apparatus enables cancellation of the phase noise at the OFDM subcarrier frequencies so that it is not necessary to allow extra spacing among subcarriers, and spectral efficiency is thereby increased.

[0018] In an embodiment, the optical delay apparatus is arranged to apply the delay to the first optical carrier signal before the first optical carrier signal is modulated by the optical modulation apparatus and to apply the delay to at least the −n optical harmonic signal before the optical combiner combines the −n optical harmonic signal with the selected +n optical harmonic signal.

[0019] The optical delay apparatus advantageously enables the introduced delay to affect only the electrical noise of one of the optical harmonic signals that are combined to produce the output photonic RF signal, while maintaining the optical correlation of the two optical harmonic signals when they are combined.

[0020] In an embodiment, the optical delay element is a bi-directional delay element configured to apply the delay, τ, to optical signals. The bi-directional delay element is provided within an optical path section. The optical path section is included in the first optical path to apply the delay to the first optical carrier signal and the optical path section is

included in the second optical path to apply the delay to at least the −n optical harmonic signal.

[0021] The bi-directional delay element may enable the apparatus to have a compact footprint.

[0022] In an embodiment, the apparatus further comprises a first delay element and a second delay element. The first delay element is provided in the first optical path before the first optical modulator and is configured to apply a delay, τ, to the first optical carrier signal. The second delay element is provided in the second optical path after the second optical modulator and is configured to apply the delay, τ, to at least the −n optical harmonic signal.

[0023] In an embodiment, the optical delay apparatus is a tunable optical delay apparatus. The delay, τ, can thus be increased or decreases and the apparatus is thus advantageously able to account for carrier spacing flexibility in 5G with a single design, avoiding hardware variants.

[0024] In an embodiment, the RF signal generation apparatus comprises a first RF signal generator and a second RF signal generator. The first RF signal generator is operable to generate a first RF signal ($V_1(t)$) at the initial frequency, f_e, having a first phase, $\phi_{e1}(t)$. The second RF signal generator is operable to generate a second RF signal ($V_2(t)$ at the initial frequency, f_e, having a second phase, $\phi_{e2}(t)$, uncorrelated to the first phase. The optical modulation apparatus comprises a first optical modulator and a second optical modulator. The first optical modulator is driven by the first RF signal ($V_1(t)$ and the second optical modulator is driven by the second RF signal ($V_2(t)$). The first optical modulator is operable to modulate the first optical carrier signal and the second optical modulator is operable to modulate the second optical carrier signal.

[0025] By generating the harmonics using two different optical modulators, driven by independent RF synthesizers providing the same electrical frequency, f_e, but with the phases uncorrelated, a uniform reduction (i.e. independent of frequency), of the phase noise from the electrical RF drive signals is achieved as compared to using a single RF signal generator to drive both optical modulators. Use of two independent RF signal generators ensures that the phases of the first and second RF signals are fully uncorrelated.

[0026] In an embodiment, the apparatus further comprises a first optical path and a second optical path. The first optical path is from the optical splitter to the optical combiner for the first optical carrier signal. The first optical path includes the first optical modulator and the first optical filter. The second optical path is from the optical splitter to the optical combiner for the second optical carrier signal. The second optical path includes the second optical modulator and the second optical filter.

[0027] In an embodiment, the first and second optical filters are tunable optical filters. The first and second optical filters can advantageously be tuned to transmit a selected order optical harmonic signal of the plurality of optical harmonic signals.

[0028] In an embodiment, the first and second optical filters are configured to select one of a first order to a tenth order optical harmonic signal of the plurality of optical harmonic signals.

[0029] In an embodiment, the initial RF frequency, f_e, is in the range 5-15 GHZ.

[0030] In an embodiment, the optical splitter, the optical modulation apparatus, the first and second optical filters, and the optical combiner are fabricated as a silicon photonic integrated circuit.

[0031] In an embodiment, the apparatus further comprises a plurality of optical splitters configured to split the optical beat signal to form a plurality of output photonic RF signals. The apparatus advantageously enables distribution of the photonic RF signal to a plurality of locations, such as the RF integrated circuits, RFICs, of an array of antenna elements.

[0032] In an embodiment, the plurality of optical splitters are arranged in a plurality of splitting stages. At least a second one of the plurality of splitting stages is followed by an amplification stage comprising a plurality of optical amplifiers arranged to amplify respective optical beat signals. The apparatus advantageously enables distribution of the photonic RF signal to a large number of locations, such as the RF integrated circuits, RFICs, of an array of antenna elements.

[0033] Corresponding embodiments and advantages apply to the communications network node, the RF signal multiplication apparatus and the methods described below.

[0034] An aspect of the invention provides a communications network node comprising photonic radio frequency, RF, signal generation apparatus. The photonic RF signal generation apparatus comprises a coherent optical source, an optical splitter, RF signal generation apparatus, optical modulation apparatus, a first optical filter, a second optical filter and an optical combiner. The coherent optical source is operable to output a coherent optical signal at a carrier frequency, f_0. The optical splitter is arranged to split the coherent optical signal into a first optical carrier signal and a second optical carrier signal. The RF signal generation apparatus is operable to generate at least one RF signal (V(t) at an initial frequency, f_e. The optical modulation apparatus is driven by the at least one RF signal and is operable to modulate the first optical carrier signal and the second optical carrier signal at the initial frequency to generate a plurality of optical harmonic signals around each optical carrier signal. The first optical filter is configured to select an nth order optical harmonic signal of a first sign, +n, of the plurality of optical harmonics around the first optical carrier signal. The second optical filter configured to select the nth order optical harmonic signal of an opposite sign, −n, of the plurality of optical harmonics around the second optical carrier signal. The optical combiner is arranged to combine the selected +n optical harmonic signal with the selected −n optical harmonic signal to generate an optical beat signal forming an output photonic RF signal.

[0035] In an embodiment, the node is one of a baseband unit or a remote radio unit. A baseband unit, BBU, is thus advantageously enabled to provide a photonic RF signal to an antenna element of a remote radio unit, RRU, or an RRU is advantageously enabled to provide a photonic RF signal to an antenna element of the RRU.

[0036] Corresponding embodiments and advantages apply to the corresponding method described below.

[0037] An aspect provides a communications network antenna element comprising an optical input, a photodetector and a radio frequency integrated circuit, RFIC. The optical input is for receiving a photonic RF signal comprising an optical beat signal. The photodetector is configured to detect the optical beat signal and output a corresponding

electrical signal at an RF frequency, $2nf_e$. The RFIC is configured to receive the electrical signal.

[0038] The antenna element may advantageously receive a low phase-noise, high frequency RF signal for use by its RFIC.

[0039] In an embodiment, the electrical signal forms a reference clock signal for the RFIC. The antenna element may advantageously receive a low phase-noise, high frequency reference clock signal for use by its RFIC.

[0040] Corresponding embodiments and advantages apply to the corresponding method described below.

[0041] An aspect of the invention provides radio frequency, RF, signal multiplication apparatus comprising a coherent optical source, an optical splitter, RF signal generation apparatus, optical modulation apparatus, a first optical filter, a second optical filter, an optical combiner and a photodetector. The coherent optical source is operable to output a coherent optical signal at a carrier frequency, f_0. The optical splitter is arranged to split the coherent optical signal into a first optical carrier signal and a second optical carrier signal. The RF signal generation apparatus is operable to generate at least one RF signal (V(t) at an initial frequency, f_e. The optical modulation apparatus is driven by the at least one RF signal and is operable to modulate the first optical carrier signal and the second optical carrier signal at the initial frequency to generate a plurality of optical harmonic signals around each optical carrier signal. The first optical filter is configured to select an nth order optical harmonic signal of a first sign, +n, of the plurality of optical harmonics around the first optical carrier signal. The second optical filter configured to select the nth order optical harmonic signal of an opposite sign, −n, of the plurality of optical harmonics around the second optical carrier signal. The optical combiner is arranged to combine the selected +n optical harmonic signal with the selected −n optical harmonic signal to generate an optical beat signal forming an output photonic RF signal. The photodetector is configured to receive the photonic RF signal and configured to detect the optical beat signal and output a corresponding electrical signal at a multiplied RF frequency, $2nf_e$.

[0042] The apparatus enables generation of a photonic RF signal in which optical phase noise is reduced or cancelled and phase noise introduced by the optical modulation apparatus is a pure multiple of the phase noise of the RF signal at the initial frequency. The apparatus thus advantageously enables the total phase noise of the multiplied RF signal to be reduced as compared to the prior art, without requiring any modulation drive signal feedback mechanism. The apparatus may advantageously enable a high-frequency RF signal to be produced from the multiplication of a low frequency oscillator or synthesizer, without adding any extra optical noise. The apparatus may advantageously provide a stable low noise RF signal even at the higher frequencies being demanded by new wireless communications technologies such as 5G New Radio. The use of photonic generation means that the generated RF signal may be more accurate, less noisy and more stable. The RF signal can be carried optically over long distances before conversion into an electrical RF signal which eliminates the electromagnetic interference that an electrical RF signals would otherwise be subject to.

[0043] In an embodiment, the electrical signal forms a reference clock signal.

[0044] In an embodiment, the multiplied RF frequency, $2nf_e$, is in the frequency range 70-120 GHZ.

[0045] In an embodiment, the apparatus further comprises a radio frequency integrated circuit, RFIC, configured to receive the electrical signal.

[0046] Corresponding embodiments and advantages apply to the corresponding method described below.

[0047] An aspect of the invention provides a method of generating a multiplied radio frequency, RF, signal. The method comprises steps as follows. A coherent optical signal is generated at a carrier frequency, f_0. The coherent optical signal is split into a first optical carrier signal and a second optical carrier signal. At least one initial RF signal is generated at an initial frequency, f_e. The first optical carrier signal is modulated using the at least one initial RF signal at the initial frequency to generate a plurality of optical harmonic signals around the first optical carrier signal. An nth order optical harmonic signal of a first sign, +n, of the plurality of optical harmonic signals around the first optical carrier signal is selected. The second optical carrier signal is modulated using the initial RF signal at the initial frequency to generate said plurality of optical harmonic signals around the second optical carrier signal. The nth order optical harmonic signal of an opposite sign, −n, of the plurality of optical harmonic signals around the second optical carrier signal is selected. The selected +n optical harmonic signal is combined with the selected −n optical harmonic signal to generate an optical beat signal forming an output photonic RF signal. The photonic RF signal is received, the optical beat signal is detected and a corresponding electrical signal at a multiplied RF frequency, $2nf_e$, is output

[0048] In an embodiment, the electrical signal forms a reference clock signal.

[0049] In an embodiment, the multiplied RF frequency, $2nf_e$, is in the frequency range 70-120 GHz.

[0050] An aspect of the invention provides a method of generating a photonic radio frequency, RF, signal. The method comprises steps as follows. A coherent optical signal is generated at a carrier frequency, f_0. The coherent optical signal is split into a first optical carrier signal and a second optical carrier signal. At least one initial RF signal is generated at an initial frequency, f_e. The first optical carrier signal is modulated using the at least one initial RF signal at the initial frequency to generate a plurality of optical harmonic signals around the first optical carrier signal. An nth order optical harmonic signal of a first sign, +n, of the plurality of optical harmonic signals around the first optical carrier signal is selected. The second optical carrier signal is modulated using the initial RF signal at the initial frequency to generate said plurality of optical harmonic signals around the second optical carrier signal. The nth order optical harmonic signal of an opposite sign, −n, of the plurality of optical harmonic signals around the second optical carrier signal is selected. The selected +n optical harmonic signal is combined with the selected −n optical harmonic signal to generate an optical beat signal forming a photonic RF signal. The photonic RF signal is transmitted.

[0051] In an embodiment, the method further comprises apply a delay, t, to optical signals. The delay is applied to the first optical carrier signal and to at least the −n optical harmonic signal.

[0052] In an embodiment, the delay, t, is applied to the first optical carrier signal before modulating the first optical carrier signal, and the delay, t, is applied to at least the −n

optical harmonic signal before combining the −n optical harmonic signal with the selected +n optical harmonic signal.

[0053] An aspect of the invention provides a method at communications network antenna element. The method comprises steps as follows. A photonic RF signal comprising an optical beat signal is received. The optical beat signal is detected. A corresponding electrical signal at an RF frequency, $2nf_e$, is output to a radio frequency integrated circuit, RFIC, of the antenna element.

[0054] In an embodiment, the electrical signal forms a reference clock signal for the RFIC. Embodiments of the invention will now be described, by way of example only, with reference to the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

[0055] FIGS. **1** to **8** are block diagrams illustrating embodiments of photonic radio frequency, RF, signal generation apparatus;

[0056] FIGS. **9** and **10** are block diagrams illustrating embodiments of communications network nodes;

[0057] FIGS. **11** and **12** are block diagrams illustrating embodiments of communications network antenna elements;

[0058] FIGS. **11**A, **13** and **16** are block diagrams illustrating embodiments of RF signal multiplication apparatus;

[0059] FIG. **12** is a block diagram illustrating an embodiment of a remote radio unit, RRU;

[0060] FIGS. **14** and **15** show simulation results;

[0061] FIG. **17** shows experimental results; and

[0062] FIGS. **18** to **20** are flowcharts illustrating embodiments of method steps.

DETAILED DESCRIPTION

[0063] The same reference numbers will be used for corresponding features in different embodiments.

[0064] An embodiment provides photonic RF signal generation apparatus **100** as illustrated in FIGS. **1***a* and **1***b*. The apparatus comprises a coherent optical source **102**, an optical splitter **106**, RF signal generation apparatus **108**, optical modulation apparatus **110**, a first optical filter **116**, a second optical filter **126** and an optical combiner **130**.

[0065] The coherent optical source comprises a laser operable to output a coherent optical signal, E(t), **104** at a carrier frequency, f_0:

$$E(t) = E_o \cos[2\pi f_o t + \phi_o(t)]$$

where E_0 is the amplitude of the electric field of the optical carrier and $\phi_0(t)$ is the phase noise of the optical carrier.

[0066] The optical splitter **106** is arranged to split the coherent optical signal into a first optical carrier signal, which follows the upper path in FIG. **1***a*, and a second optical carrier signal, which follows the lower path.

[0067] The RF signal generation apparatus **108** comprises an RF signal generator, for example, an electrical RF synthesizer, is operable to generate an RF signal (V(t) at an initial frequency, f_e:

$$V(t) = V_e \cos[2\pi f_e t + \phi_e(t)]$$

where V_e is the amplitude of the electric field of the RF signal and ϕ_e (t) is the electrical phase noise of the RF signal.

[0068] The optical modulation apparatus **110** is driven by the RF signal and is operable to modulate the first optical carrier signal and the second optical carrier signal at the initial frequency, f_e, to generate a plurality of optical harmonic signals **114** around each optical carrier signal, as illustrated in FIG. **1***b* and the insets **114** of FIG. **1***a*. Corresponding sets of optical harmonic signals are produced on either side of the each optical carrier signal; the harmonics are increasing multiples of the modulation frequency and are spaced by the modulation frequency, in this case the initial frequency, f_e, on both sides of the carrier frequency, f_0.

[0069] The first optical filter **116** is configured to select an nth order optical harmonic signal **118** of a first sign, +n, of the plurality of optical harmonics around the first optical carrier signal, i.e. the nth order harmonic, f_o+nf_e, on the right of the carrier frequency, f_0. That is to say, the first optical filter is configured to transmit at a frequency, $f=f_o+nf_e$

[0070] The second optical filter **126** is configured to select the corresponding nth order optical harmonic signal **128** of an opposite sign, −n, of the plurality of optical harmonics around the second optical carrier signal, i.e. the nth order harmonic, f_o-nf_e, on the left of the carrier frequency, f_0. That is to say, the second optical filter is configured to transmit at a frequency,

$$f = f_o - nf_e$$

[0071] The optical combiner **130** is arranged to combine the selected +n optical harmonic signal with the selected −n optical harmonic signal to generate an optical beat **132** signal forming an output photonic RF signal:

$$E(t) = E_o J_n(\beta)\{\cos[2\pi(f_0 - nf_e)t + \phi_o(t) - n\phi_e(t)] + \cos[2\pi(f_0 + nf_e)t + \phi_o(t) + n\phi_e(t)]\}$$

[0072] where:

- **[0073]** E_o is the amplitude of the electric field of the optical carrier
- **[0074]** J_n is Bessel function of the first kind of order n
- **[0075]** β is the modulation index that depends on the characteristics of the modulator:

$$\beta = \frac{\pi}{2V_\pi} V_e$$

for an amplitude modulator and

$$\beta = \frac{\pi}{V_\pi} V_e$$

for a phase modulator, where V_e is the amplitude of the electrical drive signal and V_π is the half-wave voltage

[0076] $\phi_o(t)$ is the phase noise of the optical carrier

[0077] $\phi_e(t)$ is the phase noise of the electric signal that drives the modulator

[0078] The phase noise of the optical carrier signal is cancelled due to the coherence of the coherent optical source that transfers the same phase noise to the optical harmonics. The electrical phase noise, from the RF signal, is multiplied, so that the photonics RF signal includes a pure multiplication of the electrical phase noise by a multiplication factor that depends on the order of the optical harmonics that are combined. Then the power spectral density of the phase noise associated with the optical beat signal is related to the original phase noise of the RF signal, $S_{\phi_e}(f)$, as

$$S_\phi(f) = S_{\phi_e}(f)(2n)^2 \quad \text{(Equation 1)}$$

[0079] In an embodiment, illustrated in FIG. **2**, the optical modulation apparatus comprises a bi-directional optical modulator **212**. The photonic RF generation apparatus **200** of this embodiment further comprises a first optical path from the optical splitter **106** to the optical combiner **130** for the first optical carrier signal and a second optical path from the optical splitter to the optical combiner for the second optical carrier signal.

[0080] The first optical path (indicated by dashed arrows), which may be formed in optical waveguides or by optical fibres, comprises a first optical circulator **212**, a path section **210** including the bi-directional optical modulator **212**, a second optical circulator **222** and the first optical filter **116**. The bi-directional optical modulator is operable to modulate the first optical carrier signal propagating in a first direction (indicated by the dashed arrows), as described above.

[0081] The second optical path (indicated by solid arrows), which may also be formed in optical waveguides or by optical fibres, comprises the second optical circulator **222**, the path section **210** including the bi-directional optical modulator **212**, the first optical circulator **212** and the second optical filter **126**. The bi-directional optical modulator **212** is further operable to modulate the second optical carrier signal propagating in a second, opposite direction (indicated by the solid arrows), as described above.

[0082] First and second optical splitters **312**, **322** may be used instead of optical circulators, as in the photonic RF generation apparatus **300** illustrated in FIG. **3**. The coherent optical source would be provided with an isolator in front of the laser, to protect the laser from backwards travelling optical signals from the optical splitters.

[0083] In an embodiment, illustrated in FIG. **4**, the optical modulation apparatus comprises a first optical modulator **412** and a second optical modulator **422**. The photonic RF generation apparatus **400** of this embodiment further comprises a first optical path **410** from the optical splitter **106** to the optical combiner **130** for the first optical carrier signal and a second optical path **420** from the optical splitter to the optical combiner for the second optical carrier signal.

[0084] The first optical path, which may be formed in optical waveguides or by optical fibres, comprises the first optical modulator **412** and the first optical filter **116**. The first optical modulator **412** is operable to modulate the first optical carrier signal, as described above. The second optical path, which may also be formed in optical waveguides or by optical fibres, comprises the second optical modulator **422** and the second optical filter **126**. The second optical modulator is operable to modulate the second optical carrier signal, as described above.

[0085] In an embodiment, as illustrated in FIG. **5**, the photonic RF signal generation apparatus **500** further comprises optical delay apparatus **502** arranged to apply a delay, t, to optical signals. The optical delay apparatus is arranged to apply the delay to the first optical carrier signal and to apply the delay to at least the −n optical harmonic signal. The optical delay apparatus in this embodiment is a bi-directional delay element **502**, provided within the first optical path and the second optical path as described above with reference to FIG. **2**. The bi-directional delay element is configured to apply a delay, τ, to optical signals transmitted through it in either direction. The first optical path (indicated by dashed arrows), comprises the first optical circulator **212**, a path section **510** including the bi-directional optical modulator **212** and the bi-directional delay element **502**, the second optical circulator **222** and the first optical filter **116**. The bi-directional delay element **502** applies a delay, τ, to the first optical carrier signal propagating in a first direction (indicated by the dashed arrows). The delay is therefore applied to the first optical carrier signal before it is modulated by the bi-directional optical modulator **212**.

[0086] The second optical path (indicated by solid arrows) comprises the second optical circulator **222**, the path section **510** including the bi-directional optical modulator **212** and the bi-directional delay element **502**, the first optical circulator **212** and the second optical filter **126**. The bi-directional delay element **502** applies the same delay, τ, to the second optical carrier signal and its optical harmonic signals propagating in the second, opposite direction (indicated by the solid arrows).

[0087] The optical delay apparatus is thus arranged to apply the delay to the first optical carrier signal before the first optical carrier signal is modulated by the optical modulator **212** and to apply the delay to at least the −n optical harmonic signal before it is combined in the optical combiner **130** with the selected +n optical harmonic signal.

[0088] Applying the delay to the first carrier signal before modulation and to the optical harmonic generated from the second carrier signal, i.e. after modulation of the second carrier signal, means that the delay only affects the electrical phase noise of one of the combined optical harmonic signals, i.e. the one selected from the second optical carrier's optical harmonics, while maintaining the optical correlation of the two optical harmonic signals that are combined to form the optical beat signal, thus maintaining the optical phase noise cancellation.

[0089] The phase noise of the optical carrier signal is cancelled due to the coherence of the coherent optical source that transfers the same phase noise to the optical harmonics, as described above.

[0090] First and second optical splitters may be used instead of the first and second optical circulators. The coherent optical source would be provided with an isolator in front of the laser, to protect the laser from backwards travelling optical signals from the optical splitters.

[0091] In an embodiment, the bi-directional delay element **502** is a tunable delay element. The delay, τ, can therefore

be increased or decreased to a required delay in order to generate a phase noise spectrum including notches as required.

[0092] In an embodiment, as illustrated in FIG. **6**, the photonic RF signal generation apparatus **600** further comprises optical delay apparatus arranged to apply a delay, τ, to optical signals. The optical delay apparatus is arranged to apply the delay to the first optical carrier signal and to apply the delay to at least the −n optical harmonic signal. The optical delay apparatus in this embodiment comprises a first delay element **610** and a second delay element **620**. The first delay element is provided in the first optical path **410**, as described above with reference to FIG. **4**, and the second delay element is provided in the second optical path **420**.

[0093] The first delay element **610** is provided before the first optical modulator **412** and configured to apply a delay, z, to the first optical carrier signal **104**. The second delay element **620** is provided after the second optical modulator **422** and the second optical filter **126**, and is configured to apply the delay, t, to the selected −n optical harmonic signal, f_o-nf_e **128**, transmitted by the second optical filter **126**.

[0094] The optical combiner **130** is arranged to combine the selected +n optical harmonic signal with the selected −n optical harmonic signal to generate an optical beat **132** signal forming an output photonic RF signal:

$$E(t) = E_o J_n(\beta)\left\{\cos\left[2\pi f_0(t-\tau) + 2\pi n f_e t + \phi_o(t-\tau) + n\phi_e(t) + n\frac{\pi}{2}\right] + \cos\left[2\pi(f_0 - nf_e)(t-\tau) + \phi_o(t-\tau) - n\phi_e(t-\tau) - n\frac{\pi}{2}\right]\right\},$$

[0095] where:

[0096] E_o is the amplitude of the electric field of the optical carrier

[0097] J_n is Bessel function of the first kind of order n

[0098] β is the modulation index that depends on the characteristics of the modulator:

$$\beta = \frac{\pi}{2V_\pi}V_e$$

for an amplitude modulator and

$$\beta = \frac{\pi}{V_\pi}V_e$$

for a phase modulator, where V_e is the amplitude of the electrical drive signal and V_π is the half-wave voltage

[0099] $\phi_o(t)$ is the phase noise of the optical carrier

[0100] $\phi_e(t)$ is the phase noise of the electric signal that drives the modulator

[0101] Then the power spectral density of the phase noise associated with the optical beat signal is related to the original phase noise of the RF signal, $S_{\phi_e}(f)$, as

$$S_\phi(f) = S_{\phi_e}(f)(2n)^2\cos^2(\pi\tau f)$$

which shows that it is possible to cancel the phase noise locally by setting the proper delay. This enables notches **1400** to be created in the phase noise spectrum, as shown in FIG. **14**.

[0102] The optical delay apparatus is thus arranged to apply the delay to the first optical carrier signal before the first optical carrier signal is modulated by the first optical modulator **412** and to apply the delay to at least the −n optical harmonic signal before it is combined in the optical combiner **130** with the selected +n optical harmonic signal.

[0103] Applying the delay to the first carrier signal before modulation and to the optical harmonic generated from the second carrier signal, i.e. after modulation of the second carrier signal, means that the delay only affects the electrical phase noise of one of the combined optical harmonic signals, i.e. the one selected from the second optical carrier's optical harmonics, while maintaining the optical correlation of the two optical harmonic signals that are combined to form the optical beat signal, thus maintaining the optical phase noise cancellation.

[0104] In an embodiment, the first optical filter **116** and the second optical filter **126** are tunable optical filters. The order of optical harmonic signals that are selected for combination into the optical beat signal can therefore be varied according to the desired multiplication of the initial frequency of the RF signal driving the optical modulation apparatus.

[0105] In an embodiment, the first optical filter **116** and the second optical filter **126** are configured to select one of a first order to a tenth order optical harmonic signal of the plurality of optical harmonic signals. A multiplication of up to ten times the initial frequency of the RF signal driving the optical modulation apparatus can thus be achieved.

[0106] In an embodiment, the initial RF frequency, f_e, is in the range 5-15 GHZ.

[0107] In an embodiment, the optical splitter **106**, the optical modulation apparatus **110**, **212**, **412**, **422**, the first optical filter **116**, the second optical filter **126**, and the optical combiner **130** are fabricated as a silicon photonic integrated circuit.

[0108] Referring to FIG. **7**, an embodiment provides photonic RF signal generation apparatus **650** in which the RF signal generation apparatus comprises a first RF signal generator, for example an electrical RF synthesizer **652**, and a second RF signal generator, an electrical RF synthesizer **654**.

[0109] The first RF signal generator is operable to generate a first RF signal ($V_1(t)$ at the initial frequency, f_e, having a first phase, ϕ_{e1} (t):

$$V_1(t) = V_e\cos[2\pi f_e t + \phi_{e1}(t)]$$

[0110] The second RF signal generator is operable to generate a second RF signal ($V_2(t)$) at the initial frequency, f_e, having a second phase, $\phi_{e2}(t)$, uncorrelated to the first phase:

$$V_2(t) = V_e\cos[2\pi f_e t + \phi_{e2}(t)]$$

[0111] The optical modulation apparatus comprises a first optical modulator **662** driven by the first RF signal ($V_1(t)$

and a second optical modulator **672** driven by the second RF signal ($V_2(t)$. The first optical modulator is operable to modulate the first optical carrier signal and the second optical modulator is operable to modulate the second optical carrier signal.

[0112] The RF signal generation apparatus **650** of this embodiment further comprises a first optical path **660** and a second optical path **670**. The first optical path is for the first optical carrier signal and extends from the optical splitter to the optical combiner. The first optical path includes the first optical modulator **662** and the first optical filter **116**. The second optical path is for the second optical carrier signal and extends from the optical splitter to the optical combiner. The second optical path includes the second optical modulator **672** and the second optical filter **126**.

[0113] The laser **102** generates an optical carrier at frequency f_o. The electrical field of the optical carrier is given by:

$$E(t) = E_o \cos[2\pi f_o t + \phi_o(t)]$$

[0114] The first optical filter **116** is configured to select an nth order optical harmonic signal **118** of a first sign, +n, of the plurality of optical harmonics around the first optical carrier signal, i.e. the nth order harmonic, f_o+nf_e, on the right of the carrier frequency, f_0. That is to say, the first optical filter is configured to transmit at a frequency, $f=f_o+nf_e$

[0115] The second optical filter **126** is configured to select the corresponding nth order optical harmonic signal **128** of an opposite sign, −n, of the plurality of optical harmonics around the second optical carrier signal, i.e. the nth order harmonic, f_o-nf_e, on the left of the carrier frequency, f_0. That is to say, the second optical filter is configured to transmit at a frequency,

$$f = f_o - nf_e$$

[0116] The optical combiner **130** is arranged to combine the selected +n optical harmonic signal with the selected −n optical harmonic signal to generate an optical beat **132** signal forming an output photonic RF signal. When the output photonic RF signal is detected by a square-law photodiode, the output is given by:

$$I(t) \propto \cos[2\pi(2nf_e)t + \phi(t)]$$

$$\text{where } \phi(t) = 2n\frac{\phi_{e1}(t) + \phi_{e2}(t)}{2}$$

[0117] the power spectral density of the phase noise associated with the optical beat signal is related to the original phase noises of the first and second RF signals can be expressed as

$$S_\phi(f) = n^2\left(S_{\phi_{e1}}(f) + S_{\phi_{e2}}(f)\right)$$

[0118] where $S_{\phi_{e1}}(f)$ and $S_{\phi_{e2}}(f)$ are the power spectral densities of the phase noise of the first and second RF signals respectively.

[0119] In the case where the two electrical RF synthesizers have similar quality, i.e., they produce two phase noise terms with the same power spectral density $S_{\phi_{e1}}(f)=S_{\phi_{e2}}(f)=S_{\phi_e}(f)$, the power spectral density of the phase noise associated with the optical beat signal can be expressed as

$$S_\phi(f) = 2n^2 S_{\phi_e}(f)$$

[0120] This is a factor of two lower than the power spectral density of the phase noise noise associated with the optical beat signal in the above embodiments having a single RF signal generator, described above.

[0121] By generating the harmonics using two different optical modulators, driven by independent RF synthesizers providing the same electrical frequency, f_e, but with the phases uncorrelated, a uniform reduction (i.e. independent of frequency), of the phase noise from the electrical RF drive signals is achieved as compared to using a single RF signal generator to drive both optical modulators. Use of two independent RF signal generators ensures that the phases of the first and second RF signals are fully uncorrelated.

[0122] This embodiment implements the following steps:

[0123] A coherent optical source (e.g. a laser) is split into two optical carriers each travelling along a different optical path. Each carrier is sent to an optical modulator, in a configuration in which different, uncorrelated electrical RF signals drive the two optical modulators with a modulation frequency, f_e.

[0124] A set of harmonics is generated in each carrier by the optic modulators with a non-linear characteristic. The group of harmonics, also named 'comb' are multiples of the modulation frequency f_e. The two RF signal generators are set to the same frequency f_e.

[0125] Selection of one harmonic in each optical branch via a filter, all other harmonics are substantially eliminated. To guarantee the reduction of phase noise the harmonic selected in the first carrier has to be of the same order of the harmonic selected in the second carrier, but opposite in sign: e.g. order n in the first carrier and −n in the second carrier

[0126] The two carriers are merged to generate a beat signal from the harmonic n and −n, and the beat signal is photodetected to output an electric signal at the RF frequency.

[0127] In an embodiment, the first optical filter **116** and the second optical filter **126** are tunable optical filters. The order of optical harmonic signals that are selected for combination into the optical beat signal can therefore be varied according to the desired multiplication of the initial frequency of the RF signal driving the optical modulation apparatus.

[0128] In an embodiment, the first optical filter **116** and the second optical filter **126** are configured to select one of a first order to a tenth order optical harmonic signal of the plurality of optical harmonic signals. A multiplication of up to ten times the initial frequency of the RF signal driving the optical modulation apparatus can thus be achieved.

[0129] In an embodiment, the initial RF frequency, f_e, is in the range 5-15 GHZ.

[0130] In an embodiment, the optical splitter **106**, the optical modulation apparatus **662**, **672**, the first optical filter **116**, the second optical filter **126**, and the optical combiner **130** are fabricated as a silicon photonic integrated circuit.

[0131] In an embodiment, as illustrated in FIG. **8**, the photonic RF signal generation apparatus **700** further comprises a plurality of optical splitters **702**, **704**, **706**, **708** configured to split the optical beat signal to form a plurality of output photonic RF signals **720**.

[0132] The optical splitters are arranged in a plurality of splitting stages. The first splitting stage comprises a 1:2 splitter **702**, the second splitting stage comprises two 1:4 splitters **704**, the third splitting stage comprises eight 1:4 splitters **706** and the fourth splitting stage comprises thirty-two 1:4 splitters **708**. The optical beat signal **132** output from the photonic RF signal generator **300**, is therefore split into 128 output photonic RF signals **720**.

[0133] The second splitting stage is followed by an amplification stage comprising a plurality of optical amplifiers **710** arranged to amplify respective optical beat signals. In this example, eight erbium doped fiber amplifiers **710** pumped by two 900 nm pump sources **712** are provided after the splitters **704**. The amplifiers provide a gain, G, of 20 dB; this is sufficient to overcome a 9 dB loss between the first and second stage splitters, and amplify the eight split signals to 16 dBm, to pre-compensate for a 12 dB loss between the third and fourth stage splitters. A 5 dBm optical beat signal **132** is thereby split into 128 output photonic RF signals **720** each of 4 dBm power.

[0134] This configuration is advantageous since a single RF generator, and thus a single photonic RF signal generator, is able to feed **128** antenna element RFICs. The cost and power consumption is therefore split among the antenna elements so that it is comparable to (or lower than) the power consumption of a state of the art phase locked loop operating in this frequency range, since one phase locked loop is required for each RFIC.

[0135] An embodiment, illustrated in FIG. **9**, provides a communications network node **800** comprising photonic RF signal generation apparatus **100**. It will be appreciated that any of the photonic RF signal generation apparatus **200**, **300**, **400**, **500**, **600** described above may alternatively be used in the node **800**.

[0136] An embodiment, illustrated in FIG. **10**, provides a communications network node **900** comprising photonic RF signal generation apparatus **700**, as described above.

[0137] The communications network nodes **800**, **900** may be a baseband unit, BBU, or may be a remote radio unit, RRU.

[0138] An embodiment, illustrated in FIG. **11**, provides a communications network antenna element **1000** comprising an optical input **1006**, a photodetector **1002** and a radio frequency integrated circuit, RFIC, **1004**.

[0139] The optical input is for receiving a photonic RF signal comprising an optical beat signal. The photodetector is configured to detect the optical beat signal and to output a corresponding electrical signal **1008** at an RF frequency, $2nf_e$. The RFIC is configured to receive the electrical signal.

[0140] In an embodiment, the electrical signal **1008** forms a reference clock signal for the RFIC **1004**.

[0141] In an embodiment, as illustrated in FIG. **11**A, provides RF signal multiplication apparatus **1050**, comprising the communications network antenna element **1000** of FIG. **10** combined with the photonic RF signal generation apparatus **100** of FIG. **1**. It will be appreciated that any of the photonic RF signal generation apparatus **200**, **300**, **400**, **500**, **600** described above may alternatively be used.

[0142] An embodiment, illustrated in FIG. **12**, provides a remote radio unit, RRU, of a communications network. The RRU comprises a plurality, for example 128, of antenna elements **1150**.

[0143] Each antenna element **1150** comprises an optical input **1006**, a photodetector, PD, **1002**, and an RFIC **1004**, as described above. The optical input **1006** is for receiving a photonic RF signal **720** comprising an optical beat signal. In addition, each antenna element comprises a transimpedance amplifier, TIA, **1102** arranged to amplify the output from the photodetector to form the output electrical signal **1008** sent to the RFIC.

[0144] An embodiment, illustrated in FIG. **13**, provides RF signal multiplication apparatus **1200** comprising RF signal generation apparatus, **100**, as described above, and a photodetector **1202**.

[0145] The photodetector is configured to:

- [0146] receive the photonic RF signal;
- [0147] detect the optical beat signal; and
- [0148] output a corresponding electrical signal at a multiplied RF frequency, $2nf_e$.

[0149] In an embodiment, the multiplied RF frequency, $2nf_e$, is in the frequency range 70-120 GHz.

[0150] In an embodiment, the RF signal multiplication apparatus comprises RF signal generation apparatus **600** as described above with reference to FIG. **6**.

[0151] In this embodiment, the laser **102** generates an optical carrier signal, E(t), at a carrier frequency f_o:

$$E(t) = E_o \cos[2\pi f_o t + \phi_o(t)]$$

[0152] The electrical RF generator **108** generates an RF signal, V(t), at an initial frequency f_e:

$$V(t) = V_e \cos[2\pi f_e t + \phi_e(t)]$$

[0153] The delay elements **610**, **620** introduce a delay t (to be optimised depending on the RF source characteristics). The optical modulators (which may be phase or amplitude modulators) are driven by the RF signal, V(t). The optical filters **116**, **126** select a single one of the optical harmonic signals ($f=f_o \pm nf_e$ in the upper/lower branch). The photodetector, which may be a photodiode, performs photodetection of the beat signal formed by the combination of the selected optical harmonic signals and generates an electrical signal at a frequency $f_{out}=2nf_e$

[0154] In an embodiment, the RF signal multiplication apparatus is implemented in silicon photonics using photonic waveguides to route the optical carrier signals through the different elements. Integrated power splitter/combiners may be used to split and recombine the optical signals and distributed feedback Bragg reflectors, DFBR, may be used as the optical filters, for their narrow passband width, enabling an optical harmonic spacing of few GHz to be used.

[0155] The optical field of the photonic RF signal, **132**, before photodetection at the photodetector **1202** can be written as:

$$E(t) = E_o J_n(\beta)\left\{\cos\left[2\pi f_o(t-\tau) + 2\pi n f_e t + \phi_o(t-\tau) + n\phi_e(t) + n\frac{\pi}{2}\right] + \cos\left[2\pi(f_0 - nf_e)(t-\tau) + \phi_o(t-\tau) - n\phi_e(t-\tau) - n\frac{\pi}{2}\right]\right\},$$

[0156] where:

[0157] E_o is the amplitude of the electric field of the optical carrier

[0158] J_n is Bessel function of the first kind of order n

[0159] β is the modulation index that depends on the characteristics of the modulator:

$$\beta = \frac{\pi}{2V_\pi} V_e$$

for an amplitude modulator and

$$\beta = \frac{\pi}{V_\pi} V_e$$

for a phase modulator, where V_e is the amplitude of the electrical drive signal and V_π is the half-wave voltage

[0160] $\phi_o(t)$ is the phase noise of the optical carrier

[0161] $\phi_e(t)$ is the phase noise of the electric signal that drives the modulator

[0162] τ is the delay applied by the delay elements

[0163] The photo-detected signal then will give an output electrical signal proportional to

$$I(t) \propto \cos[2\pi(2nf_e)t + \phi(t) + \theta]$$

where $\theta = 2\pi \cdot 2nf_e\tau + n\pi$ is a constant phase. The direct current, DC, terms that would be removed by DC blocks in the photodiode and the high frequency terms ($\sim 2f_0$) that would be out of the photodiode bandwidth have been removed.

[0164] Given the initial frequency f_e generated by the RF generator, the output electrical signal will be at a frequency that is multiplied by 2n times. The phase noise, $\phi(t)$, of the output electrical signal is given by:

$$\phi(t) = n(\phi_e(t) + \phi_e(t-\tau))$$

From which it can be seen that the phase noise of the output electrical signal depends on the delay introduced to the first optical carrier signal before it is modulated by the optical modulator **412**. From this, the spectral density of the phase noise of the output electrical signal is given by

$$S_\phi(f) = S_{\phi_e}(f)(2n)^2 \cos^2(\pi\tau f)$$

It is therefore possible to cancel the phase noise of the output electrical signal for certain frequencies by applying an appropriate delay. Notches may therefore be produced in the phase noise spectrum of the output electrical signal, as illustrated in FIGS. **13** and **14**.

[0165] FIG. **14** shows a simulation of the power spectral density of the phase noise (normalized to the power of the optical beat signal) obtained from the multiplication of an RF source via the generation of two optical harmonics. FIG. **15** shows a comparison of the phase noise spectrum of an output electrical signal from the RF signal generation apparatus and the phase noise spectrum of a multiplied RF signal generated without the phase noise cancellation implemented in the RF signal generation apparatus. The thick curve is the result that would be obtained without noise cancellation and the thin curve is that obtained with noise cancellation.

[0166] In this simulation: the delay is τ=0.4 μs, the fifth order optical harmonic signals ($f=f_o \pm 5f_e$) are used, the initial frequency generated by the RF generator is f_e=5 GHz. The notches have a spacing, f_m, of 240 kHz.

[0167] The phase noise power spectral density is:

$$L_{opt}\left(\frac{dBc}{\text{Hz}}\right) = L_e\left(\frac{dBc}{\text{Hz}}\right) + 20\log(2n) + 10\log\left[\cos^2(\pi\tau f)\right]$$

It can be seen from FIG. **15** that, without the decoupling of the electric phase noise, the electric phase noise is multiplied by 2n, resulting in the term 20 log(2n) of the above equation. The term 10 log $[\cos^2(\pi\tau f)]$ is the additional term coming from introducing the delay in one optical path before modulation of the first carrier signal. This term can be made negative to compensate for the electrical noise to cancel the noise for given values of frequency, i.e. the notches shown in FIG. **15**. The frequencies for which the noise cancels out can be conveniently chosen to correspond to subcarrier locations, by selecting the appropriate value of t to fit with the subcarrier spacing.

[0168] The optical filters **116**, **126** are configured to exclude spurious frequencies from the other optical harmonics near the selected one. The optical filters thus preferably have a transmission bandwidth that is narrower than the optical harmonic spacing. The choice of the modulation frequency then is related to the characteristics of the optical filters that are used. A convenient choice for implementation could be a modulation frequency, i.e. an RF signal, V(t), having an initial frequency, f_e, in the range of 5-15 GHz which allows to exploit the advantages of low noise frequency multiplication while allowing optical filtering with, for example narrowband DFBRs. The multiplied RF frequency, $2nf_e$, is in the frequency range 70-120 GHZ.

[0169] The RF signal multiplication apparatus advantageously enables a high-frequency RF carrier to be produced by the multiplication of a low frequency oscillator or synthesizer, without adding any extra phase noise and reducing the phase noise inherited from the low-frequency oscillator.

[0170] The apparatus enables deep notches to be formed in the phase noise profile out the output electrical signal at selected frequencies, f_m (where f_m is the distance from the carrier frequency), that substantially cancel the phase noise locally and produce an overall decrease of the phase noise. The location of the notches can be selected by controlling the amount of delay τ applied to the first optical carrier so that they correspond to the zeros of the function $\cos^2(\tau\pi f_m)$. For an OFDM transmission scheme, the apparatus enables phase noise to be cancelled at the subcarrier frequencies so that it is not necessary to allow extra spacing between subcarriers and spectral efficiency is increased. The delay t

can be tuned to account for carrier spacing flexibility in 5G with a single design, avoiding hardware variants.

[0171] An embodiment, illustrated in FIG. **16**, provides RF signal multiplication apparatus **1250** comprising RF signal generation apparatus, **650**, as described above, and a photodetector **1202**.

[0172] The photodetector **1202** is configured to:

[0173] receive the photonic RF signal;

[0174] detect the optical beat signal; and

[0175] output a corresponding electrical signal at a multiplied RF frequency, $2nf_e$.

[0176] In an embodiment, the multiplied RF frequency, $2nf_e$, is in the frequency range 70-120 GHz.

[0177] FIG. **17** illustrates experimental results obtained using the RF signal multiplication apparatus **1250**, to generate an electrical RF carrier at 110 GHz. The RF signal generators **652**, **654** of the RF signal generation apparatus **650** were configured to generate first and second RF signals at initial frequency, f_e, of 18.3 GHZ and the first and second optical filters **116**, **126** were configured to select the 3^{th} order harmonics, i.e. $f=f_o+3f_e$ and $f=f_o-3f_e$, to multiply the initial frequency by a factor of 6.

[0178] The curves shown in FIG. **17** compare the case where a single RF signal generator, i.e. a single RF signal (clock) is used to drive the two modulators and the case where each modulator is driven by a different RF signal generator, i.e. two RF signals (clocks) with uncorrelated phase, as in the RF signal generation apparatus **650**. The theoretical curve for two uncorrelated RF signals is shown for comparison. The reduction of phase noise is about 3 dB, i.e. 50%, in agreement with the modelling discussed above. Referring to FIG. **18**, an embodiment provides a method **1500** of generating a multiplied radio frequency, RF, signal. The method comprises generating **1502** a coherent optical signal at a carrier frequency, f_0. The coherent optical signal is split **1504** into a first optical carrier signal and a second optical carrier signal.

[0179] An initial RF signal is generated **1506** at an initial frequency, f_e.

[0180] The first optical carrier signal is modulated **1508** using the initial RF signal at the initial frequency to generate a plurality of optical harmonic signals around the first optical carrier signal. An nth order optical harmonic signal of a first sign, +n, is selected from the plurality of optical harmonic signals around the first optical carrier signal.

[0181] The second optical carrier signal is also modulated **1512** using the initial RF signal at the initial frequency to generate the same plurality of optical harmonic signals around the second optical carrier signal. The same, nth, order optical harmonic signal of the opposite sign, −n, is selected **1514** from the plurality of optical harmonic signals around the second optical carrier signal.

[0182] The selected +n optical harmonic signal is combined **1516** with the selected −n optical harmonic signal to generate an optical beat signal forming an output photonic RF signal. The photonic RF signal is received **1518**, the optical beat signal is detected and a corresponding electrical signal at a multiplied RF frequency, $2nf_e$, is output.

[0183] In an embodiment, a first RF signal ($V_1(t)$) is generated at the initial frequency, f_e, having a first phase, $\phi_{e1}(t)$, and a second RF signal ($V_2(t)$) is generated at the initial frequency, f_e, having a second phase, ϕ_{e2} (t), uncorrelated to the first phase. The first optical carrier signal is modulated using the first RF signal ($V_1(t)$) and the second optical carrier signal is modulated using the second RF signal ($V_2(t)$).

[0184] In an embodiment, the electrical signal forms a reference clock signal.

[0185] In an embodiment, the multiplied RF frequency, $2nf_e$, is in the frequency range 70-120 GHz.

[0186] Referring to FIG. **19**, an embodiment provides a method **1600** of generating a radio frequency, RF, signal. This method may be performed at a communications network node. The method comprises generating **1502** a coherent optical signal at a carrier frequency, f_0. The coherent optical signal is split **1504** into a first optical carrier signal and a second optical carrier signal.

[0187] An initial RF signal is generated **1506** at an initial frequency, f_e.

[0188] The first optical carrier signal is modulated **1508** using the initial RF signal at the initial frequency to generate a plurality of optical harmonic signals around the first optical carrier signal. An nth order optical harmonic signal of a first sign, +n, is selected from the plurality of optical harmonic signals around the first optical carrier signal.

[0189] The second optical carrier signal is also modulated **1512** using the initial RF signal at the initial frequency to generate the same plurality of optical harmonic signals around the second optical carrier signal. The same, nth, order optical harmonic signal of the opposite sign, −n, is selected **1514** from the plurality of optical harmonic signals around the second optical carrier signal.

[0190] The selected +n optical harmonic signal is combined **1516** with the selected −n optical harmonic signal to generate an optical beat signal forming an output photonic RF signal, and the photonic RF signal is transmitted **1602**.

[0191] In an embodiment, the method further comprises applying a delay, τ, to the first optical carrier signal before modulating the first optical carrier signal, and applying the delay, τ, to the selected −n optical harmonic signal before combining with the selected +n optical harmonic signal.

[0192] Referring to FIG. **20**, an embodiment provides a method **1700** at an antenna element. The method comprises receiving **1702** a photonic RF signal comprising an optical beat signal. The optical beat signal is detected **1704** and a corresponding electrical signal at an RF frequency, $2nf_e$, is output to a radio frequency integrated circuit, RFIC, of the antenna element.

[0193] In an embodiment, the electrical signal forms a reference clock signal for the RFIC.

1. A photonic radio frequency, RF, signal generation apparatus comprising:

a coherent optical source operable to output a coherent optical signal at a carrier frequency, f_0;

an optical splitter arranged to split the coherent optical signal into a first optical carrier signal and a second optical carrier signal;

RF signal generation apparatus configured to generate at least one RF signal (V(t)) at an initial frequency, f_e;

optical modulation apparatus driven by the at least one RF signal and configured to modulate the first optical carrier signal and the second optical carrier signal at the initial frequency to generate a plurality of optical harmonic signals around each optical carrier signal;

a first optical filter configured to select an nth order optical harmonic signal of a first sign, +n, of the plurality of optical harmonics around the first optical carrier signal;

a second optical filter configured to select the nth order optical harmonic signal of an opposite sign, −n, of the plurality of optical harmonics around the second optical carrier signal; and

an optical combiner arranged to combine the selected +n optical harmonic signal with the

selected −n optical harmonic signal to generate an optical beat signal forming an output photonic RF signal; and

an optical delay apparatus arranged to apply a delay, z, to optical signals, the optical delay apparatus being arranged to apply the delay to the first optical carrier signal before the first optical carrier signal is modulated by the optical modulation apparatus and to apply the delay to at least the −n optical harmonic signal before the optical combiner combines the −n optical harmonic signal with the selected +n optical harmonic signal.

2. (canceled)

3. The photonic RF signal generation apparatus as claimed in claim **1**, wherein the optical modulation apparatus comprises a bi-directional optical modulator and wherein the apparatus further comprises:

a first optical path from the optical splitter to the optical combiner for the first optical carrier signal, the first optical path including:

a path section including the bi-directional optical modulator operable to modulate the first optical carrier signal propagating in a first direction;

the optical delay apparatus; and

the first optical filter; and

a second optical path from the optical splitter to the optical combiner for the second optical carrier signal, the second optical path including:

the path section including the bi-directional optical modulator further configured to modulate the second optical carrier signal propagating in a second, opposite direction;

the optical delay apparatus; and

the second optical filter.

4. The photonic RF signal generation apparatus as claimed in claim **1**, wherein the optical modulation apparatus comprises a first optical modulator configured to modulate the first optical carrier signal and a second optical modulator configured to modulate the second optical carrier signal and wherein the apparatus further comprises:

a first optical path from the optical splitter to the optical combiner for the first optical carrier signal, the first optical path including the first optical modulator, the optical delay apparatus and the first optical filter; and

a second optical path from the optical splitter to the optical combiner for the second optical carrier signal, the second optical path including the second optical modulator, the optical delay apparatus and the second optical filter.

5. (canceled)

6. (canceled)

7. The photonic RF signal generation apparatus as claimed in claim **1**, wherein the optical delay apparatus is a bi-directional delay element configured to apply the delay, τ, to optical signals, the bi-directional delay element provided within an optical path section included in the first optical path to apply the delay to the first optical carrier signal and included in the second optical path to apply the delay to at least the −n optical harmonic signal.

8. The photonic RF signal generation apparatus as claimed in claim **7**, wherein the optical delay apparatus comprises:

a first delay element provided in the first optical path before the first optical modulator and configured to apply the delay, «, to the first optical carrier signal; and

a second delay element provided in the second optical path after the second optical modulator and configured to apply the delay, τ, to at least the −n optical harmonic signal.

9. The photonic RF signal generation apparatus as claimed in claim **8**, wherein the optical delay apparatus is a tunable optical delay apparatus.

10. The photonic RF signal generation apparatus as claimed in claim **1**, wherein:

the RF signal generation apparatus comprises a first RF signal generator operable to generate a first RF signal ($V_1(t)$) at the initial frequency, f_e, having a first phase, $\phi_{e1}(t)$, and a second RF signal generator operable to generate a second RF signal ($V_2(t)$) at the initial frequency, f_e, having a second phase, $\phi_{e2}(t)$, uncorrelated to the first phase; and

the optical modulation apparatus comprises a first optical modulator driven by the first RF signal ($V_1(t)$) and a second optical modulator driven by the second RF signal ($V_2(t)$), wherein the first optical modulator is operable to modulate the first optical carrier signal and the second optical modulator is operable to modulate the second optical carrier signal.

11. (canceled)

12. The photonic RF signal generation apparatus as claimed in claim **1**, wherein the first and second optical filters are tunable optical filters.

13. The photonic RF signal generation apparatus as claimed in claim **1**, wherein the first and second optical filters are configured to select one of a first order to a tenth order optical harmonic signal of the plurality of optical harmonic signals.

14. The photonic RF signal generation apparatus as claimed in claim **1**, wherein the initial RF frequency, f_e, is in the range 5-15 GHz.

15. (canceled)

16. The photonic RF signal generation apparatus as claimed in claim **1**, further comprising a plurality of optical splitters configured to split the optical beat signal to form a plurality of output photonic RF signals.

17. The photonic RF signal generation apparatus as claimed in claim **16**, wherein the plurality of optical splitters are arranged in a plurality of splitting stages and wherein at least a second one of the plurality of splitting stages is followed by an amplification stage comprising a plurality of optical amplifiers arranged to amplify respective optical beat signals.

18. The photonic RF signal generation apparatus as claimed in claim **1**, wherein the photonic RF signal generation apparatus is comprised in a communications network node.

19.-**21**. (canceled)

22. A radio frequency, RF, signal multiplication apparatus comprising:

a coherent optical source operable to output a coherent optical signal at a carrier frequency, f_0;

an optical splitter arranged to split the coherent optical signal into a first optical carrier signal and a second optical carrier signal;

RF signal generation apparatus operable to generate at least one RF signal (V(t)) at an initial frequency, f_e;

optical modulation apparatus driven by the at least one RF signal and configured to modulate the first optical carrier signal and the second optical carrier signal at the initial frequency to generate a plurality of optical harmonic signals around each optical carrier signal;

a first optical filter configured to select an nth order optical harmonic of a first sign, +n, of the plurality of optical harmonics around the first optical carrier signal;

a second optical filter configured to select the nth order harmonic signal of an opposite sign, −n, of the plurality of optical harmonic signals around the second optical carrier signal;

an optical combiner arranged to combine the selected +n optical harmonic signal with the selected −n optical harmonic signal to generate an optical beat signal forming an output photonic RF signal; and

a photodetector configured to receive the photonic RF signal and configured to detect the optical beat signal and output a corresponding electrical signal at a multiplied RF frequency, $2nf_e$;

an optical delay apparatus arranged to apply a delay, τ, to optical signals, the optical delay apparatus being arranged to apply the delay to the first optical carrier signal before the first optical carrier signal is modulated by the optical modulation apparatus and to apply the delay to at least the −n optical harmonic signal before the optical combiner combines the −n optical harmonic signal with the selected +n optical harmonic signal.

23. The RF signal multiplication apparatus as claimed in claim **22**, wherein the multiplied RF frequency, $2nf_e$, is in the frequency range 70-120 GHz.

24. The RF signal multiplication apparatus as claimed in claim **22**, further comprising a radio frequency integrated circuit, RFIC, configured to receive the electrical signal.

25. A method of generating a multiplied radio frequency, RF, signal, the method comprising:

generating a coherent optical signal at a carrier frequency, f_0;

splitting the coherent optical signal into a first optical carrier signal and a second optical carrier signal;

generating at least one initial RF signal at an initial frequency, f_e;

modulating the first optical carrier signal using the at least one initial RF signal at the initial frequency to generate a plurality of optical harmonic signals around the first optical carrier signal;

selecting an nth order optical harmonic signal of a first sign, +n, of the plurality of optical harmonic signals around the first optical carrier signal;

modulating the second optical carrier signal using the at least one initial RF signal at the initial frequency to generate said plurality of optical harmonic signals around the second optical carrier signal;

selecting the nth order optical harmonic signal of an opposite sign, −n, of the plurality of optical harmonic signals around the second optical carrier signal;

combining the selected +n optical harmonic signal with the selected −n optical harmonic signal to generate an optical beat signal forming an output photonic RF signal; and

receiving the photonic RF signal and detecting the optical beat signal and outputting a corresponding electrical signal at a multiplied RF frequency, $2nf_e$; and applying a delay, τ, to the first optical carrier signal and applying the delay to at least the −n optical harmonic signal, the delay, τ, being applied to the first optical carrier signal before modulating the first optical carrier signal and the delay, τ, is applied to the −n optical harmonic signal before combining with the selected +n optical harmonic signal.

26. A method of generating a photonic radio frequency, RF, signal, the method comprising:

generating a coherent optical signal at a carrier frequency, f_0;

splitting the coherent optical signal into a first optical carrier signal and a second optical carrier signal;

generating at least one initial RF signal at an initial frequency, f_e;

modulating the first optical carrier signal using the at least one initial RF signal at the initial frequency to generate a plurality of optical harmonic signals around the first optical carrier signal;

selecting an nth order optical harmonic signal of a first sign, +n, of the plurality of optical harmonic signals around the first optical carrier signal;

modulating the second optical carrier signal using the at least one initial RF signal at the initial frequency to generate said plurality of optical harmonic signals around the second optical carrier signal;

selecting the nth order optical harmonic signal of an opposite sign, −n, of the plurality of optical harmonic signals around the second optical carrier signal;

combining the selected +n optical harmonic signal with the selected −n optical harmonic signal to generate an optical beat signal forming a photonic RF signal;

transmitting the photonic RF signal; and

applying a delay, τ, to the first optical carrier signal and applying the delay to at least the −n optical harmonic signal, the delay, τ, being applied to the first optical carrier signal before modulating the first optical carrier signal and the delay, τ, is applied to the −n optical harmonic signal before combining with the selected +n optical harmonic signal.

27. (canceled)

28. (canceled)

29. The method of claim **26**, wherein generating the at least one initial RF signal comprises generating a first RF signal ($V_1(t)$) at the initial frequency, f_e, having a first phase, $\phi_{e1}(t)$, and generating a second RF signal ($V_2(t)$) at the initial frequency, f_e, having a second phase, $\phi_{e2}(t)$, uncorrelated to the first phase, and wherein the first optical carrier signal is modulated using the first RF signal ($V_1(t)$) and the second optical carrier signal is modulated using the second RF signal ($V_2(t)$).

30. (canceled)

* * * * *