Fast and Broadband SOI Photonic Integrated Microwave Phase Shifter

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Abstract: An integrated silicon-on-insulator microwave photonic phase shifter based on an optical deinterleaver and a reverse-biased pn-junction waveguide providing broadband phase shift up to more than 400° with fast reconfiguration time of 1 ns is demonstrated.

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1. Introduction

Microwave-photonic phase shifters (MWP-PSs) enable processing of radio-frequency (RF) signals in radio-over-fiber communications, sensing, and defense systems, with the advantages of broadband and high RF operation, large phase-shift ranges, and immunity to electromagnetic interference with regard to their electronic counterparts. Additionally, a fast response time is an appealing feature for forthcoming 5G systems, where fast MWP-PSs can be for instance exploited to implement rapidly reconfiguring beam-steering operation in phased-array antennas. For practical system applications, on-chip integration is also desirable due to increased stability, drastically minimized size and weight, and low operating power of photonic-integrated circuits (PICs). To this aim, several PICs implementing MWP-PSs have been proposed in the last recent years [1-4], none of them simultaneously matching the demand for wide phase-shift range, broad bandwidth, low in-band power oscillations, ultra-fast (i.e., sub-μs) reconfiguration time, and compatibility with CMOS integrated circuits fabrication technology.

Here, we present a photonic-integrated MWP-PS realized in CMOS-compatible silicon-on-insulator (SOI) technology, performing stable phase shifts well in excess of 360° over a bandwidth of 6 GHz for RF carriers spanning in the X- and Ku-band, with in-band power variations within 1 dB and fast response time below 1 ns.

2. Integrated MWP-PS Operation Principle, Implementation, and Results

The schematic operation of the MWP-PS is shown in Fig. 1(a); the circuit comprises an optical deinterleaver filter (ODF), an optical phase shifter (OPS), an optical coupler (OC), and balanced photodiodes (BPDs). A single-sideband (SSB) modulated optical signal is generated by sending the light from a laser source (LS) at the optical frequency ν_c to a SSB electro-optic modulator (EOM), driven by a microwave signal centered at f_{RF}. Within the PIC, the ODF spatially separates the optical carrier from the signal sideband. After the ODF, the isolated optical carrier traverses the OPS, before being recombined with the modulated sideband and sent to BPDs. Carrier-sideband beating in the photo-detection process then translates the phase shift applied to the optical carrier by the OPS to the down-converted RF signal. A PIC, implementing the scheme in the dashed box of Fig. 1(a), has been realized in SOI

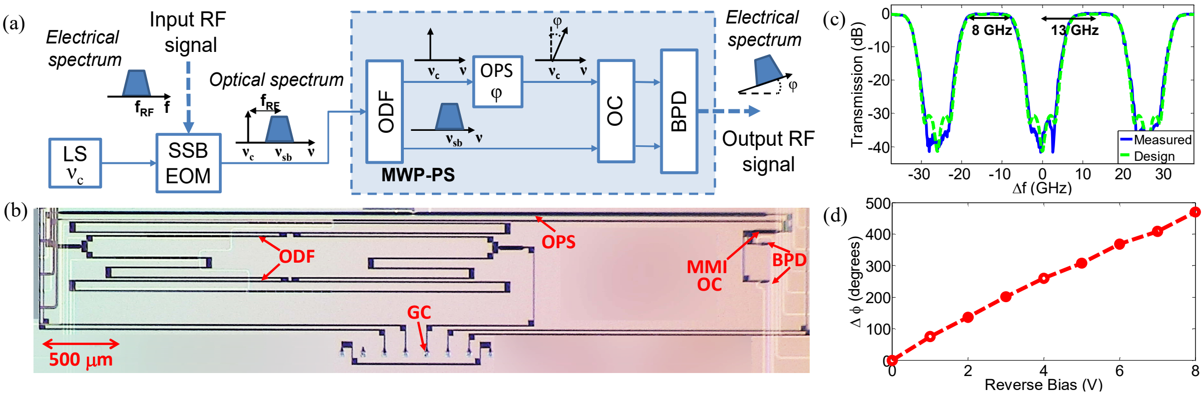

Fig. 1. (a): Microwave-photonic phase shifter (MWP-PS) operation. LS: laser source; SSB-EOM: single-sideband electro-optic modulator; ODF: optical deinterleaver filter; OPS: optical phase-shifter; OC: optical coupler; BPD: balanced photodiodes. (b): Optical image of the fabricated device. (c): Measured transmission spectrum and design simulation of the ODF; (d): Measured integrated OPS characteristic.

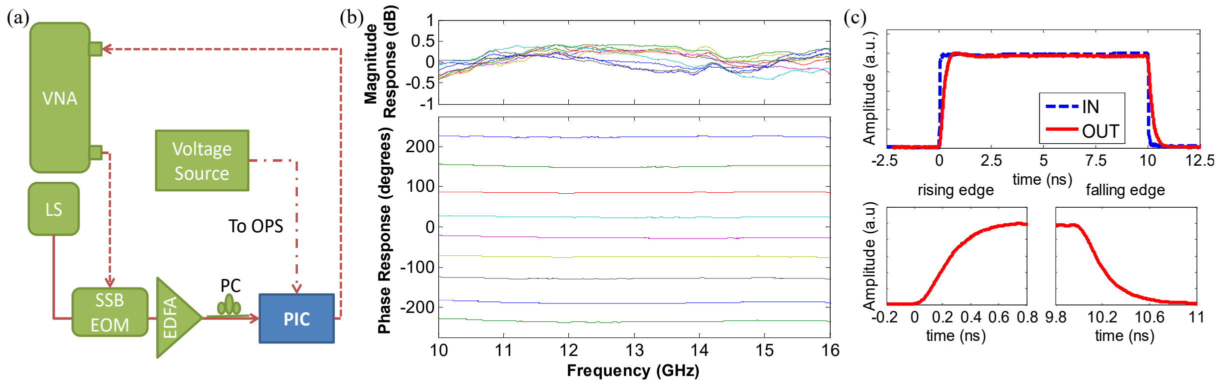

Fig. 2. (a): Set-up for MWP-PS photonic integrated chip (PIC) characterization; VNA: vector network analyzer; EDFA: erbium-doped fiber amplifier. (b): Measured RF phase response and normalized in-band gain variations vs. VNA output frequency for different values of reverse bias voltage applied to the pn-junction in the OPS. (c): OPS step-response with details of rising and falling edges.

technology through a multi-project wafer run [5]. An image of the fabricated PIC is shown in Fig. 1(b). A microring resonator-loaded Mach-Zehnder interferometer realizes the ODF. The OPS exploits carrier depletion-induced effective index modulation in a 4.25 mm-long interdigitated pn-junction embedded in a rib waveguide. A multimode-interference (MMI) OC recombines the phase-shifted optical carrier and the modulated sideband before *p-i-n* germanium BPDs with -3dB bandwidth of ~20 GHz. Grating couplers (GCs) are used for vertical coupling with the accessing optical fiber. The optical transmission spectrum of the ODF at one output port measured on a test structure is in Fig. 1(c), showing a periodic box-like transmission (free-spectral-range, FSR, ~26 GHz) with flat passband having -0.5 dB bandwidth of ~8 GHz, -30 dB stop-band width of ~6.5 GHz, and steep roll-off. The other ODF output exhibits a complementary spectrum. The measured OPS characteristic is in Fig. 1(d), where a 475° phase shift over an 8V range for the pn-junction reverse bias is measured. The integrated MWP-PS has been characterized using the set-up of Fig. 2(a); The LS optical carrier is initially tuned in the center of the ODF passband toward the OPS branch, and the output frequency from a vector network analyzer (VNA), driving the SSB-EOM, is swept over a bandwidth of 6 GHz around f_{RF}=13 GHz. Correspondingly, either the low- or high-frequency sideband generated by the SSB-EOM is transmitted by the ODF toward the lower path of Fig. 1(a). An erbium-doped fiber amplifier (EDFA) boosts the signal power at PIC input up to ~10 dBm, and a polarization controller (PC) optimizes the chip coupled power through the GC. By delivering the microwave signal from BPDs at PIC output back to the VNA, the magnitude and phase of S_{21} parameter is measured. The results, in Fig. 2(b), illustrate almost flat phase shifts in the whole 6 GHz band spanning over more than 450° for bias voltages ranging between 0 and -8V. The standard deviation of the measured phase response in the full bandwidth range stays below 1.5° over a 360° shift. Due to the box-like ODF transmission, the power oscillations over the 6 GHz span are confined within 0.8 dB. The average RF power variation for 360° phase step is ~2.5 dB. By tuning the LS at the edges of the ODF passband, similar characteristics over a 6 GHz sweep around f_{RF}=10 GHz and f_{RF}=16 GHz have been observed.

The intrinsic unit-length bandwidth of pn-junctions is of several tens of GHz, limited by lumped-electrode load resistance in long structures. The modulation bandwidth of the OPS has then been characterized by connecting the LS output to the PIC, and tuning the optical carrier such that light is almost evenly split between the two branches of the circuit, so that phase-to-intensity modulation conversion occurs when it recombines in the OC. By applying to the OPS a square-wave signal with 2V amplitude from a waveform generator, the step response of the MWP-PS has been monitored on a sampling oscilloscope. The results in Fig. 3(b) indicate a fast rising time below 1 ns.

3. Acknowledgements

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4. References

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