Fully tunable microwave photonic phase shifter for broadband signals based on a single heterogeneously integrated III-V-on-Silicon microdisk resonator

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***Abstract*—We present a novel broadband microwave photonic phase shifter based on a single III-V microdisk resonator heterogeneously integrated on a silicon-on-insulator waveguide. Fully 2π phase shift tunability is accomplished by free-carrier-induced effective index modulation.**

I. Introduction

The past years have witnessed an increasing interest in the development of generation, transport and processing tasks of radio frequency (RF), microwave and millimeter-wave signals directly in the optical domain [1]. This field of activity is known as microwave photonics (MWP) [2]. One of the applications that have focused significant efforts within the MWP field consists of the implementation of flexible filters free from bandwidth constraints [1]. To this end, the efficient design of broadband tunable microwave phase shifters is of key importance [1]. The state-of-the-art tends towards integrated CMOS-compatible approaches, especially those based on silicon-on-insulator (SOI), which lead to high-density integration [3]. However, the slow dynamics of silicon can hamper the assembly of SOI-based circuits in practice [4]. To overcome this limitation hybrid approaches based on the integration of silicon with a direct band gap compound, especially those belonging to the III-V group, stand out as a promising solution for high-speed signal processing [5]. In this paper, we present a novel broadband microwave photonic phase shifter based on an InP microdisk resonator (MDR) heterogeneously integrated on a SOI waveguide.

II. Principle of Operation

The propagation in the MDR is based on the whispering-gallery modes, which are confined to the edges of the cavity resulting in a resonant-type transfer function. The principle of operation relies on the exploitation of the phase transfer function of the MDR operated in over-coupled regime in combination with using optical single sideband (OSSB) modulation. The OSSB, composed of the optical carrier and the modulation sideband, must be accurately placed in the vicinity of a resonance. In this way, the optical carrier and the sideband experience different phase change in accordance with the MDR phase transfer function. The phase induced on the optical carrier can be controlled by altering the notch spectral position through effective index modulation enabled by carrier injection in the cavity. As a result, this fact allows for controllable phase shift tunability of the microwave signal.

III. Experimental Setup

Fig. 1(a) sketches the experimental setup of the InP/SOI MDR based MWP phase shifter. A weak spectral line centered at 1562 nm was generated by a tunable laser in continuous wave (CW). The input RF signal, $s_{in}(t)$, was imprinted on the optical carrier by means of an intensity modulator (IM) operated in dual-drive configuration, giving as a result OSSB modulation. The signal at the output of the IM was sent into the 9-μm-diameter MDR, which is molecularly bonded on top of a SOI circuit containing a 750-nm-wide and 220-nm-high Si strip waveguide. The disk-to-waveguide gap determines the coupling factor (k), which was found to be ~ 6 %. The total area, including both the input and output vertical grating couplers is ~ 0.1 mm^2 (see inset Fig. 2). More details on the fabrication of such a device are given in [5]. Both optical waves are then weighted and phase-shifted accordingly to the MDR transfer function, which can be spectrally shifted by modifying the effective index through carrier injection. To this end, a tunable voltage source was connected to the metal contacts of the MDR. Polarization controllers were inserted at both the modulator and the MDR input to avoid power penalty derived from polarization mismatching. Finally, the optical signal exiting the MDR output was detected using a high-bandwidth photodetector (HBW PD), amplified by means of a high-gain electrical amplifier (EA) and acquired by a vectorial network analyzer (VNA). In the inset of Fig. 2 a footprint image of fabricated MDRs is illustrated.

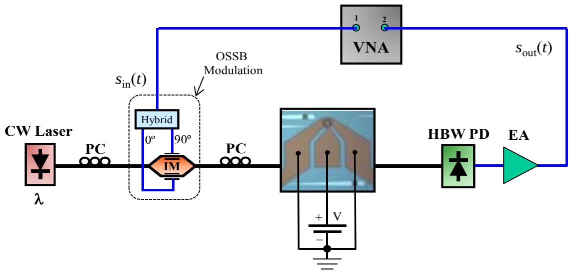

Fig. 1. Sketch showing the experimental setup.

IV. Results

The gain and phase transfer functions of the device as a function of the injected current are shown in Fig. 2. The total optical power inserted at the input vertical grating coupler was 1 dBm. The frequency of the modulating signal was adjusted from 5 to 20 GHz. The notch-type transfer function can be progressively tuned by applying different currents. It is important to notice that the notch depth depends on the current as well. By increasing the current, the roundtrip loss in the cavity decreases due to a higher gain in the III-V layer. To develop phase-shifting functionalities the over-coupled operating regime is desired since a lower power penalty compared to the critical case is featured and still 2π phase transitions in each notch are obtained. In the inset of Fig. 2, the spectral position for both the optical carrier and modulation sideband within the phase transfer function are also depicted. By sweeping the current from 1.5 to 1.725 mA, the carrier experiences a phase change of nearly 360º.

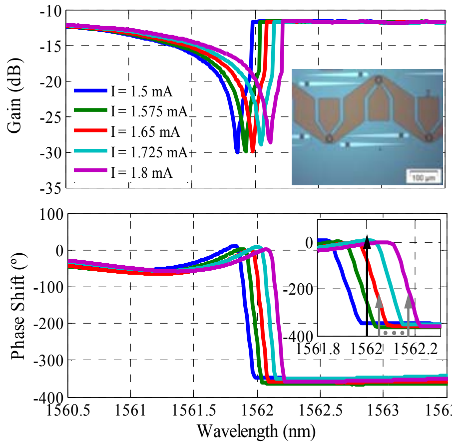

Fig. 2. Gain and phase transfer functions with the injection current.

Fig. 3 shows the results for both the phase shift and power of the detected microwave signal as a function of the injection current. It can be seen that quasi-linear and continuously tunable phase shifts are obtained. The maximum achievable phase shift at a certain frequency is limited by the abruptness of the phase slopes of the transfer function. In particular, a minimum modulating frequency of 18 GHz is required to reach a phase shift of ~ 2π radians. The functionality as a phase shifter is also demonstrated for lower frequencies, however, full 360º shifts are not obtained. According to the gain transfer function, a phase change is accompanied by a power penalty. A power variation of ~ 12 dB within the tunability range comprising from 1.5 to 1.725 mA is obtained when the modulating frequency, Ω, is 18 GHz.

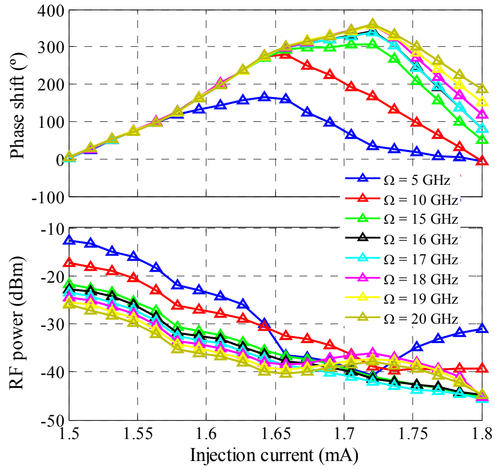

Fig. 3. RF phase shift and power as a function of the injection current for different modulating frequencies.

V. Conclusions

A novel broadband MWP phase shifter based on a single III-V/SOI MDR has been proposed and demonstrated. Quasi-linear and continuously tunable ~ 360º phase shifts have been obtained when considering radiofrequencies greater than 18 GHz. Phase shift tunability has been accomplished by modifying the effective index through carrier injection in the III-V compound. As a consequence, the tunability speed is limited by the carrier dynamics in the semiconductor, which is in the scale of hundreds of *ps*. This fact greatly improves the performance compared to other similar SOI-based approaches, in which the thermo-optic effect is used as tunable mechanism. To the best of our knowledge, it represents the smallest approach for photonic phase shifting of microwave signals reported so far.

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