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Abstract. The microwave phase shifter using 25-GHz dense wavelength division multiplexing (DWDM) channel spacing tuning on the silicon-on-insulator microring resonator (MRR), which was utilizing the multimode interference as the coupling function to achieve wavelength independence, is proposed and demonstrated. With a quality factor of 1199 for the MRR, there was 25-deg phase tuning for every 25-GHz DWDM channel spacing at 5-GHz microwave frequency. The total tunability from the microwave phase shifter could achieve 350 deg using 22 DWDM channels with 25-GHz spacing. [DOI: 10.1117/1.OE.52.10.100501]

Subject terms: phase shifts; photonics; silicon; waveguides.

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1 Introduction

The photonic generation, processing, distribution, filtering, and control of microwave and millimeter wave signals are of interests for a number of applications due to the advantages of large bandwidth, fast tunability, immunity to electromagnetic interference, and low weight of photonic components. An important component in many microwave photonics applications is a phase shifter that provides large bandwidth and fast response time. Various techniques for realizing photonic phase shifters have been demonstrated such as wavelength conversion,[1] stimulated Brillouin scattering,[2] slow light effect in semiconductor devices,[3] and cross-phase modulation.[4] Recently, a photonic microwave phase shifter utilizing a silicon-on-insulator (SOI) microring resonator (MRR) by the directional coupler, which was experimentally showing a 0-deg to 336-deg phase shifting range by the thermo-optical tuning, is proposed.[5]

In Fig. 1, the optical tap could be implemented in the dense wavelength division multiplexing (DWDM) system, formed by a multiplexer, a optical amplifier, and a demultiplexer, to fully utilize 25-GHz channel spacing for microwave phase management through the thermal tuning photonic bus.[6] Therefore, the microwave phase shifter tuning using DWDM channel spacing on SOI MRR with a wavelength-insensitive multimode interferometer (MMI) coupler was proposed and demonstrated. To meet the highest phase tuning range, the SOI MRR was designed for a low quality factor under the over-coupling condition.[5]

2 Approach and Design

The transmitted phase shift Φ and the quality factor Q of a MMI-coupled ring resonator can be derived as follows:

$$\Phi = \pi + \phi + \tan^{-1}\left(\frac{t \sin \phi}{a - t \cos \phi}\right) + \tan^{-1}\left(\frac{at \sin \phi}{1 - at \cos \phi}\right) \tag{1}$$

$$Q \equiv \frac{\lambda}{\Delta\lambda_{\mathrm{FWHM}}} \equiv \frac{\pi n_g L}{\lambda} \frac{\sqrt{at}}{1 - at}, \tag{2}$$

where a is the transmission coefficient. t^2 and $1 - t^2$ are the optical power ratios for the parallel and cross states of MMI, respectively. ϕ is the round-trip phase accumulation and represented as $\phi = 2\pi n L_R/\lambda\langle/\rho\mu\rangle$. n and L_R are the effective index and length of the ring resonator, respectively. $\lambda\langle/\rho\mu\rangle$ is the operating wavelength. n_g is the ring resonator waveguide group index, and $\Delta\lambda_{\mathrm{FWHM}}$ is the full resonant wavelength width at the half maximum.

When $1 - t^2$ owns the larger value, the Q is lower and the phase slope relative to wavelengths gets smaller. Since we need to get the broad wavelength tuning by the 25-GHz DWDM channel spacing, the large $1 - t^2$ value is expected.

The MMI, which is insensitive to the wavelength and has the large processing tolerance, is involved as the coupling function in MRR. In this article, we were using the paired interference MMI for the larger $1 - t^2$, which requires the MMI length longer than the half of the beat length. The finite difference time-domain, a direct solution for Maxwell's curl equations carried out by RSoft Fullwave, was utilized to simulate and predict the model performance of silicon-wire waveguides-based MMI coupler. Under the over-coupling condition of the broad-phase tuning range, the MMI for the transverse magnetic (TM) polarization was designed to have the length of 9.6 μm, width of 3 μm, and input/output waveguide distance as 1 μm when the silicon-wire waveguide owned the width of 0.45 μm and height of 0.26 μm. In order to get the small quality factor Q for a wide-phase tuning range, the MMI-coupled MRR was studied at four different ring resonator perimeters of 110, 220, 330, and 440 μm.

3 Experiments and Discussions

The I-line stepper lithography was implemented to fabricate the MMI-coupled MRR, which image was taken by the optical microscope camera and illustrated in the inset of Fig. 2. The scanning electronic microscope picture for silicon-wire waveguides was also demonstrated in the inset of Fig. 2. Due to the high-speed testing equipment limitation, a tunable

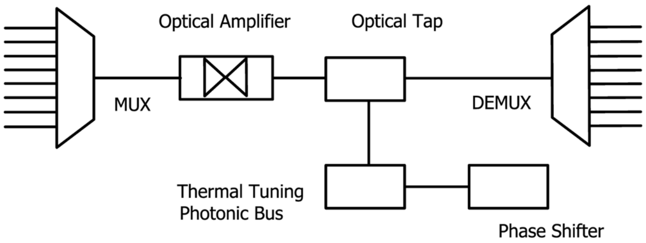

Fig. 1 The dense wavelength division multiplexing (DWDM) channel spacing tuning for microwave phase shifter in DWDM system.

laser source (TLS) was carried out with the intensity modulated 5-GHz signal by the vector network analyzer (Anritsu 37347C, Anritsu, Japan) through a Mach-Zehnder interferometer modulator, and the modulation spectrum could be monitored by an optical spectrum analyzer (OSA), as shown in Fig. 2. The double sideband (DSB) was generated from the intensity modulation of the TLS by the 5-GHz signal and observed in an Anritsu benchtop OSA (MS9740A) built with the high-optical wavelength resolution of 0.03 nm, as shown in Fig. 3. A JDS Uniphase interleaver with the model number of IBC-C05D02412 showed a free spectral range of 50-GHz between even and odd output ports. Since the 3-dB bandwidth of an individual interleaver channel was around 25 GHz, a 25-GHz DWDM channel spacing could then be aligned well to filter out one sideband either from the upper or lower side of the DSB. A TLS wavelength of 1555.96 nm was taken to demonstrate the single sideband (SSB) spectrum after the interleaver was implemented after a 5-GHz modulated DSB, as shown in Fig. 3. The TM-polarized light operated by the polarization controller was coupled in and out with respect to the device under test, MRR, by lensed fibers. Following that, one sideband of the modulated signal was filtered out through an interleaver, the signal was amplified using an erbium-doped fiber amplifier, and then detected by a photodetector. Finally, the microwave signal was analyzed and characterized by the vector network

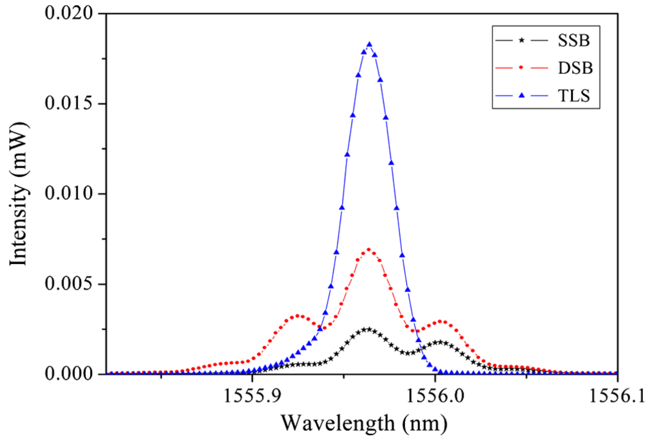

Fig. 3 The optical spectrums for tunable laser source (TLS), double sideband (DSB), and single sideband (SSB).

analyzer. In this experiment, the wavelength tuning MRR was fabricated on the SOI wafer with 260-nm thick silicon slab and a 3-μm buried silicon dioxide layer.

MMI-coupled ring resonators with four different ring resonator perimeters were characterized and shown in the inset of Fig. 4. A 110-μm perimeter of SOI MRR, utilized as the microwave phase shifter, demonstrated the smallest Q of 1199, which was calculated through the resonance wavelength of 1546 nm divided by the 1.29-nm linewidth measured from the OSA. After inserting the parameters from tested propagation loss as 30 dB/cm and TM-polarized group effective index as 4 (Ref. 7), t^2 and $1 - t^2$ were derived as 0.25 and 0.75 from Eq. (2), respectively, which are equal to the characterized splitter ratios from the stand-alone MMI structures.

The tuning operation was performed by manipulating the wavelengths through TLS. The transmission spectrum and radio frequency (RF) phase shift versus the operating wavelengths were simultaneously demonstrated in Fig. 4. The

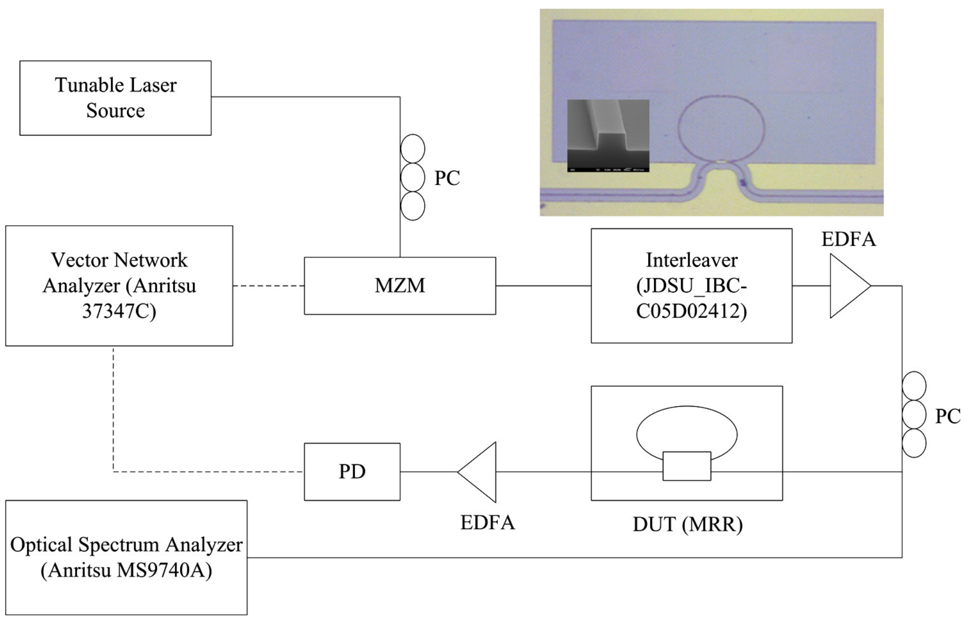

Fig. 2 Experimental setup for microwave phase shift test.

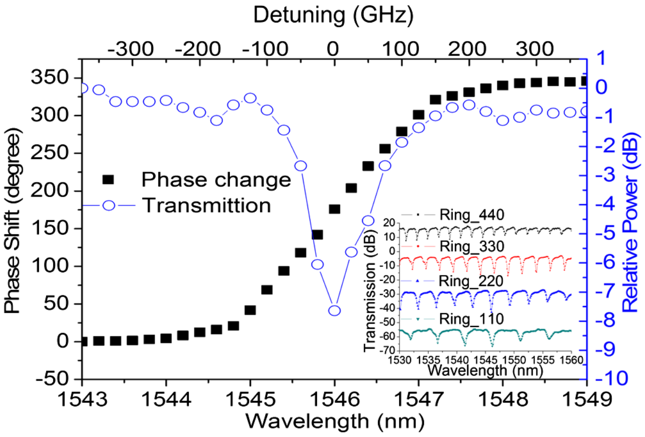

Fig. 4 Measured transmission spectrum and RF phase shift of the multimode interferometer (MMI)-based microring resonator (MRR).

tunable phase shift was showing 350 deg under 5-GHz microwave frequency. In the linear region of Fig. 4, the tuning range from −150 GHz to 150 GHz at 1546-nm central wavelength demonstrated 300-deg phase shifting between 21 deg and 321 deg. There was 25-deg phase tuning for every 25-GHz DWDM channel spacing, and the sensitivity was showing 1 deg/GHz. The total microwave phase tunability from MMI MRR could achieve 350 deg through 22 DWDM channels with 25-GHz spacing. If the phase tuning needs to be improved for less sensitivity, lower Q and larger $1 - t^2$ are necessary. From the measured 30-dB/cm propagation loss on the silicon-wire waveguide, the transmission coefficient a for the 110-μm perimeter of SOI MRR can be derived as 0.96. Compared with the derived t value of 0.5 from Eq. (2), the over-coupling condition $a > t$ for the phase shifting was also satisfied.[5]

4 Conclusions

A wide-operating wavelength range and high-fabrication tolerance for the MMI coupler had been implemented on the SOI-based MRR for microwave phase tuning function. For the highest phase tuning range, the MMI-coupled MRR was designed and fabricated with a circumference of 110 μm and a stable-quality-factor of 1199 across a wide range of wavelengths. A microwave phase tunability on SOI MRR was experimentally demonstrated on a 350-deg phase shift range at 22 channels with 25-GHz spacing, equal to 550-GHz wavelength detuning, under 5-GHz microwave frequency.

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