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Integrated vector sum microwave photonic phase shifter based on asymmetric Mach-Zendner structure in SOI

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Abstract: An integrated vector sum microwave photonic phase shifter (MWPPS) based on the asymmetric Mach-Zendner structure in Silicon on Insulator (SOI) rib waveguides was designed and fabricated for the first time. A fixed true time delay of 47 ps was achieved by a length difference of 3 983 μm between the two asymmetric arms. Then two thermo-optical Variable Optical Attenuators (VOAs) were integrated in the two arms respectively to tune the optical power individually. The phase shift ranging from 0° to near 180° for a 10 GHz microwave signal has been achieved by the RI variation of $0 \sim 6 \times 10^{-3}$ in VOAs. The device which has a very compact size could be easily integrated in silicon optoelectronic chips and expected to be widely used in Optically Controlled Phased Array Radars (OCPARs).

Key words: phase shifter; microwave photonics; Silicon on Insulator (SOI)

基于 SOI 非对称马赫曾德尔结构的集成矢量和微波光子移相器

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摘要:设计和分析了一种基于 SOI(绝缘体上的硅)脊型波导非对称马赫曾德尔结构的集成矢量和微波光子移相器。对于 10 GHz 的微波信号,设定非对称两臂的长度差为 3 983 μm 时,其相应的时间延迟约为 47 ps。分别在两臂上集成了一个热光可调谐可变光衰减器用于光学调谐,当衰减单元的折射率在 $0 \sim 6 \times 10^{-3}$ 变化时,实现了 10 GHz 微波信号在 0 ~ 180°的相位调谐。该器件尺寸小、结构紧凑,易于实现片上集成,在光控相控阵雷达中很有应用前景。

关　键　词:移相器;微波光子学;绝缘体上的硅
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1 Introduction

Microwave Photonic Phase Shifter (MWPPS) is a photonic device which is used to process the phase of a microwave signal in optical domains. It has drawn much attention in both military and satellite communications due to the advantages of compact size, light weight, high operating frequency and large simultaneous band. It plays an important role in Optically Controlled Phased Array Radars (OCPARs) for Optical Beam Forming Networks (OBFNs). And it can overcome the electronic-bottleneck and tune the phase of high frequency signal in the millimeter-wave band even in the THz domain by taking advantages of microwave and photonics. Various techniques for realizing microwave photonic phase shifters have been reported, including using Optical True-time Delay (OTTD) units[1-3], wavelength conversion in a Distributed Feedback Laser (DFB)[4], and heterodyne mixing method[5,6], vector-sum principle[7,8]. However, a practical implementation of phase arrays with thousands of elements is limited by the size and complexity of the conventional phase-shifting schemes. The use of miniaturized and integrated on-chip devices to perform this function is thus of much interest.

In this work, we provide a vector sum MWPPS based on MZ structure in SOI waveguides which can used to achieve the phase-shift from 0° to 180° for a 10 GHz signal. It features broadband operation, flexibly tunable phase-shifting range, reduced complexity, compact footprint size, easy integration. And the doubled phase shift can be achieved by adding another branch.

2 Principle and design

In the vector-sum technique, two cosine signals that have the same frequency but different amplitudes (A_1 and A_2) and phases are summed. We can control the phase of the resultant signal by changing the amplitudes of two signals:

$$A_1\cos(\omega t) + A_2\cos(\omega t + \Delta\varphi) = A\cos(\omega t + \varphi), \quad (1)$$

Where

$$A = [A_1^2 + A_2^2 + 2A_1A_2\cos(\Delta\varphi)]^{1/2}, \quad (2)$$

$$\varphi = \tan^{-1}\left[\frac{\sin(\Delta\varphi)}{A_1/A_2 + \cos(\Delta\varphi)}\right]. \quad (3)$$

As can be seen from Eq. (3), one can easily control the phase of the resultant signal by changing the amplitude ratio (A_1/A_2) of the two input signals at fixed $\Delta\varphi$.

Based on above vector-sum technique, a compact and easily implemented on-chip asymmetric Mach-Zendner structure in SOI rib waveguides is proposed, and the schematic of integrated VSM-MWPPS is shown in Fig. 1. Fig. 1(a) the is phase shifter structure and Fig. 1(b) is the cross section of the SOI waveguide.

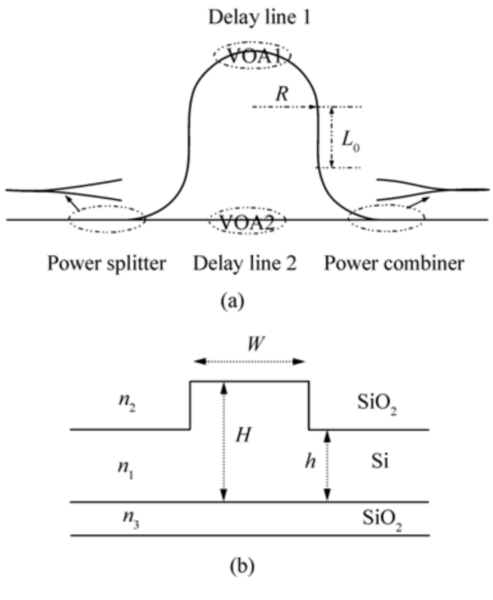

Fig. 1 (a) Basic structure of integrated VSM-MWPPS, (b) waveguide cross section

There are two important aspects needing to be considered. One is single mode transmission and the another is bend loss. From Fig. 2 (a), for H = 1.3 μm top Si, waveguide rib width of 1.1 μm and external rib height of 0.6 μm is considered to ensure single mode transmission, and from Fig. 2 (b) and (c), when R is bigger than 180 μm, less than 1 dB bend loss can be ensured. In this work R is set as 1 000 μm.

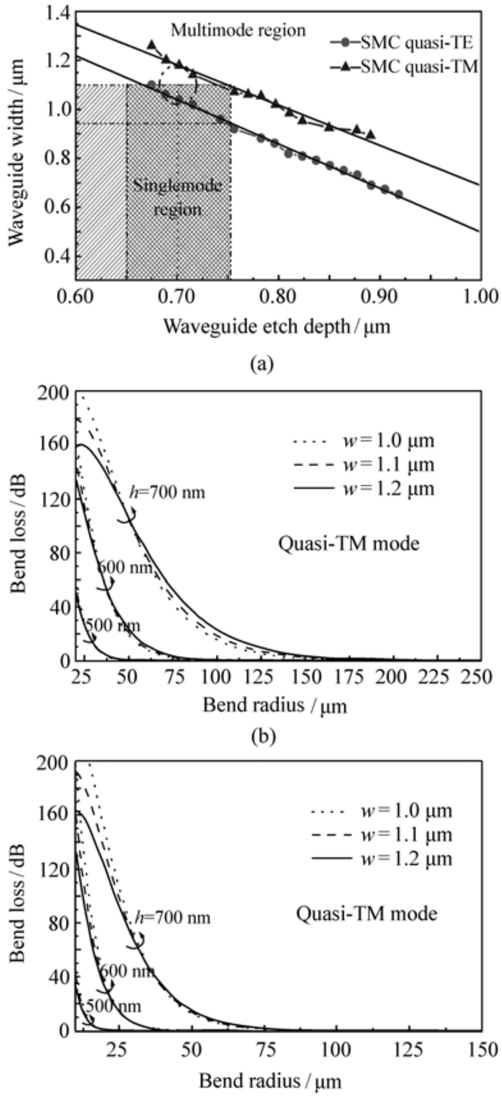

Fig. 2 (a) Determination of single mode condition, (b) and (c) the relationship between bend loss and bend radius when h is 500 nm, 600 nm and 700 nm

The maximum fixed phase shift can be expressed as the following equation:

$$\left(\frac{4\pi R + 2L_0 - 4R}{v_g}\right) \times \omega_s = \varphi, \quad (4)$$

Where R is bend radius, v_g is group velocity, ω_s is angular frequency of microwave signal. And φ is the maximum phase difference between two branches, which is determined by ω_s, R, L_0 and v_g.

In this design, φ is 175°. According to Eq. (4), when a 10 GHz microwave signal is modulated on optical carrier, the fixed length difference L_0 is calculated to be 3 983 μm. Simultaneously, to ensure single mode transmission and ignorable bend loss, the specific parameters of phase shifter are shown in Tab. 1.

Tab. 1 Device parameters

Designed parameters	Detailed values/μm
Internal rib height H	1.3
External rib height h	0.6
Rib width W	1.1
Length difference of two branches ΔS	3 983
Minimum bend radius R_{min}	1 000
Compensated waveguide length L_0	850

As can be seen from Eq. (3), by changing the amplitude ratio (A_1/A_2), φ will range from 0° to 175°. Theoretically, we can achieve any needed phase shifts by adjusting L_0 and R.

To avoid degradation and instability of the transfer function of vector sum phase shifter due to coherent interference, the wideband optical source is considered to be the carrier. A schematic diagram of the VOA which is independent to wavelength is shown in Fig. 3(a)[9]. Two gradual change tapers, designed to ensure single mode characteristic and low loss less than 1° tilting angle and 1 500 μm waveguide length, are designed to bridge the single mode and the multi-mode waveguide. A refractive index variation of Δ will be achieved by heating the thermo-optical modulation section . The smaller the tilting angle α is , the larger attenuation can be obtained with the same variation of Δ. But the desired large resolution will be unachievable. A compromised α of $3°$ is considered, which can result in 20 dB optical power attenuation when Δ increases over 6×10^{-3}. The relationships between attenuation and refractive index variation is shown in Fig. 3(b)

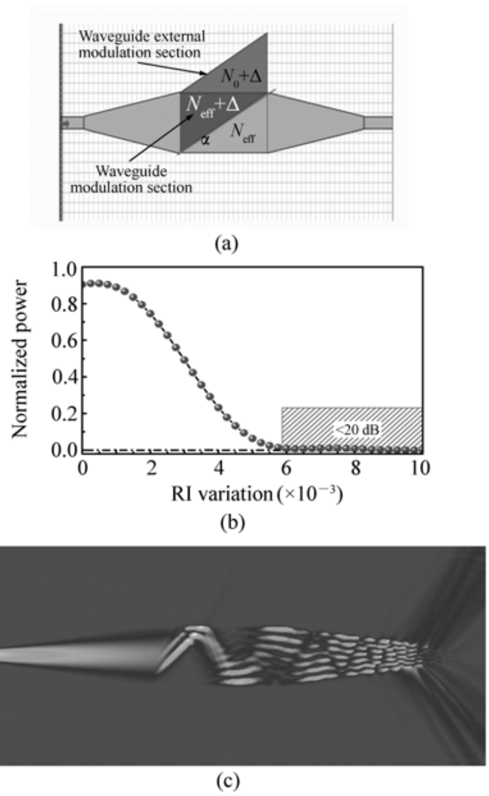

Fig. 3　(a) VOA structure, (b) stimulated normalized output optical power changing with refractive index variation, (c) stimulated optical field distribution when Δ is greater than 6×10^{-3}

and the optical distribution at 20 dB attenuation is shown in Fig. 3(c).

Theoretically analyzed phase shift result is shown in Fig. 4. As can be seen, phase shift varies with optical power ratio.

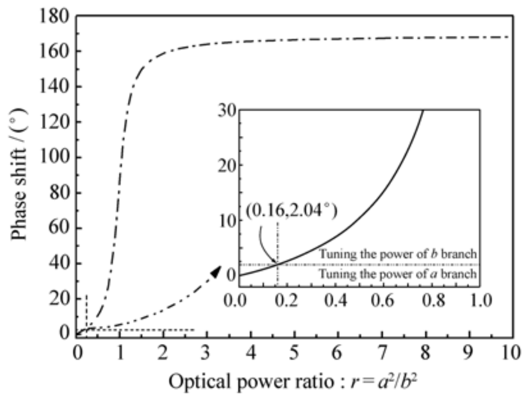

Fig. 4　Theoretically analyzed phase shift changes with optical power ratio

3　Conclusions

The designed microwave photonic phase shifter based on the asymmetric Mach-Zendner structure in SOI rib waveguides features broadband operation, flexibly tunable phase-shifting range, reduced complexity, compact footprint size, easy integration. We control the phase shift by tuning thermo-optic VOAs. Although our demonstration has no limitation in operation frequency, linear phase tuning is not readily achieved.

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