Optical 90° Hybrids Based on Silicon-on-Insulator Multimode Interference Couplers

Tingting Hong, Wei Yang, Huaxiang Yi, Xingjun Wang\(^*\), Yanping Li\(^*\), Ziyu Wang, Zhiping Zhou
State Key Laboratory of Advanced Optical Communication Systems and Networks, School of Electronics Engineering and Computer Science, Peking University, Beijing, 100871, China

ABSTRACT

An optical 90° hybrids based on silicon-on-insulator (SOI) 4×4 MMI couplers have been fabricated in 340nm top silicon using E-Beam technology. Below 2.2° phase deviation of the hybrids for the across C-band of TE mode have been simulated, which is well satisfied with the typical systems requirements. The measured optical transmission powers from port to port show that the devices function well as a 6dB power divider with excess loss around 1dB at wavelength \(\lambda=1550\text{nm}\) for TE mode. The measured transmission spectra of the 4×4 MMI coupler are seriously affected by the FP resonance noise, which bring in error in phase deviation testing.

Keywords: Optical hybrid, multimode interference, strip waveguide, silicon-on-insulator technology.

1. INTRODUCTION

In multilevel coherent transmission systems, quadrature phase shift keying (QPSK) modulation is considered as one of the efficient methods to maximize spectral efficiencies and receiver sensitivities\(^{[1]}\). Working as a demodulator of the QPSK modulated signals, an optical 90° hybrid is one of the prerequisite components in coherent receiver systems\(^{[2]}\).

In consideration of monolithic integration with photodetectors (PDs) in coherent system, there are many kinds of waveguide-based hybrids reported, such as 2×2 optical couplers and phase shifters\(^{[3, 4]}\), star couplers\(^{[5, 6]}\) or arrayed waveguide gratings (AWG)\(^{[7]}\), 4×4 multimode interference (MMI) couplers\(^{[8, 9]}\), 2×4 MMI and 2×2 MMI with phase shifters\(^{[10, 11]}\). Among these hybrid structures, a 4×4 Multimode interference coupler is one of the simplest structures to realize the function of optical 90° hybrid. In addition, it can be easy to achieve good IQ balance due to its inherent quadrature phase relationship.

Nowadays silicon-on-insulator (SOI) is an attractive platform for waveguide-based devices, because of its allowance for very compact device, and its compatibility with CMOS process. SOI-based optical hybrids have been paid attention to in the last two years\(^{[8, 9]}\). In this letter, we will show the fabrication and experimental results of 4×4 MMI couplers in SOI strip waveguide technology.

\(^*\)xjwang@pku.edu.cn and liyp@pku.edu.cn
2. 4×4 MMI COUPLERS

A 90° hybrid is a six-ports device with two inputs and four outputs, as shown in Fig. 1(a). In optical coherent receiver system, signal (S) and local oscillator (LO) are launched into the hybrid and a certain phase quadrature relationships was obtained in the output ports.

MMI couplers rely on self-imaging effect[12], which is the result of interference between a large numbers of supported modes in multimode waveguides. These modes travel with different propagation constants and interfere to form replicas of input field at certain imaging distances. Thus, an input field profile is reproduced in single or multiple images at periodic intervals along the propagation direction of the guide. In general, wider waveguides contain more supported modes than the narrower ones and get better quality of self-image. But wider waveguides might cause more excess loss at the same time.

A MMI coupler is consisted of a multimode waveguide and a number of access waveguides, through which we can launch light into and recover light from the multimode waveguide. For an N×M MMI, where N and M are the numbers of input and output waveguides, the phase relationships between inputs and outputs are inherent[13]. It appears that 4×4 MMI couplers satisfy the phase quadrature relationship, which means if there are input fields E₁ and E₃ at input ports 1 and 3, the output fields will theoretically be proportional to E₁+E₃, E₁+jE₃, E₁−jE₃ and E₁−E₃ [Fig. 1(b)]. Obviously, 4×4 MMI couplers satisfy the desired optical 90° hybrid characteristics using only six ports of eight.

Fig. 1. (a) Schematic of the optical 90° hybrid with balanced PDs; (b) 4×4 MMI coupler configured as optical 90° hybrid.

3. SIMULATION RESULTS

The 4×4 MMI couplers are simulated in 340-nm top silicon SOI wafer platform for C-band transmission system. In order to prevent crosstalk between waveguides, the width of the multimode waveguide and the access waveguides are 10μm and 1μm, so that the space between the nearest access waveguides is more than 1.5μm. The length of the multimode waveguide can be designed by \( L = n_{eff} \cdot W_{eff} / \lambda \) [13], where \( n_{eff} \) and \( W_{eff} \) are the effective index and the effective width of the multimode waveguide.

Fig. 2(a) shows that with a single input, an uniform four-fold image of the input appears at the end of the multimode waveguide. In other words, the 4×4 MMI coupler separates one light beam into four equably, acting as a 6 dB power...
A main performance of the 4×4 MMI coupler is available bandwidth. The bandwidth of an optical 90 ° hybrid is mainly limited by the phase deviation ($\Delta \phi$), which is defined as the phase difference between the ideal quadrature phase and actual phase. As shown in Fig. 2(b), the phase deviation of the 4×4 MMI coupler is below 2.2° across C-band in simulation, which satisfy the typical systems requirement ($|\Delta \phi| < 5°$).

Fig.2. (a) 4×4 MMI coupler functions as a 6 dB power divider; (b) Phase deviation simulation result of 4×4 MMI coupler.

4. FABRICATION

Our devices are fabricated in SOI strip waveguide technology with 340-nm top silicon using E-Beam lithography and ICP etching technology. The pattern needs only one E-Beam process, and etching down to the silica layer is easier to implement. Fig. 3(a) and Fig. 3(b) are the top-view SEM photographs of the 1×2 MMI coupler and the 4×4 MMI coupler.

To test the phase behavior of the 4×4 MMI coupler, a ~400GHz free spectral range of the delayed Mach-Zehnder interferometer is added before the coupler [Fig. 3(c)]. In delayed interferometer, a 1×2 MMI coupler is used and the radius of the curve waveguide is designed to be more than 50μm to avoid bend loss.

Fig. 3. The top-view SEM photographs of the 1×2 MMI coupler (a) and the 4×4 MMI coupler (b); Schematics of test structure of the 4×4 MMI coupler(c).
5. EXPERIMENTAL RESULTS

Fig. 4 shows the schematic of our test platform for the fabricated devices. We used an infrared tunable laser as a light source and the output power is set to be 9.2dBm at wavelength $\lambda=1550$nm. And the input polarization state is adjusted to be a linearly polarized TE-mode through a digital polarization controller. The light is launched into and recovered from the devices by butt coupled to a lens fiber at each side.

![Schematic of the test platform for fabricated devices.](image)

In order to estimate the excess loss of 4×4 MMI coupler, a straight waveguide, the same size with the access waveguides of 4×4 MMI coupler, is fabricated on the same sample with the couplers. As previously mentioned, a 4×4 MMI coupler functions as a 6dB power divider with a single launching light, and we check it out by testing the 4×4 MMI coupler port to port. Fig. 5(a) shows that the average optical output power of the 6dB power divider is about -26dBm with launching light of 9.2dBm, while the output power of the straight waveguide is -19.0dBm. Ignoring the transmission loss of the straight waveguide with length of multimode region, the excess loss of the 4×4 MMI coupler is around 1dB. It can be noticed that there is large coupling loss (~12dB per facet) in our testing because of the thin top silicon layer (340nm). The result can become better by ameliorating the technology of E-beam.

To measure the transmission spectra of the 4×4 MMI coupler, light is launched into the input port of the delayed interferometer and recovered from the 4 output ports of the 4×4 MMI coupler. As shown in Fig. 5(b), the output power of the four port varies periodically (~3nm) as a function of wavelength of the input light. Reducing the step spacing of the wavelength, we can clearly see that the output power is carrying a kind of noise [Fig. 5(c)], which is caused by the waveguide formed FP resonance. Seriously affected by the noise, the measurement of phase deviation of the 4×4 MMI coupler is not accurate, below ~25° across C-band, ten times bigger than the calculation results. That is because the phase deviation is ~0.008nm per degree in our case and the period of FP resonance noise is ~0.08nm. Thus, the noise added ten times of phase error in our measurement.

Steps are been taking to get rid of the influence from FP resonance noise, including fabrications and data processing. And the former is basically reducing the size of the input and output ports of the devices, through which to weaken the FP resonance effect.
Fig. 5. (a) Port to port transmission power of 4×4 MMI coupler; (b) Measured transmission spectrum of the 4×4 MMI coupler with ~400GHz delayed interferometer; (c) FP resonance noise.

6. SUMMARY

Optical 90° hybrids based on SOI multimode interference couplers have been simulated and fabricated. Simulations show that phase deviation of 4×4 MMI couplers is below 2.2° across C-band for TE mode. The experiment results show that the coupler functions well as a 6dB power divider with excess loss around 1dB. Optical delay interferometers, with 400GHz free spectral range, are added to test the phase deviation of the 4×4 MMI couplers. The measured transmission spectra of the 4×4 MMI coupler are seriously affected by the FP resonance noise, which bring in error in phase deviation testing.

ACKNOWLEDGMENT

This work is partially supported by the National High Technology Research and Development Program of China (863 Program, 2011AA010302).

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Proc. of SPIE Vol. 8255  82551Z-5


