Reduction of phase-difference deviation in 90° optical hybrid over wide wavelength range

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Abstract: We describe a technique for reducing the wavelength-dependent phase-difference deviation between in-phase and quadrature components in an 90° optical hybrid consisting of four 3-dB couplers and a phase shifter. We fabricated the 90° hybrid with our proposed technique, which uses silica-based planar lightwave circuit technology. The fabricated 90° hybrid exhibits a low phase-difference deviation from 90° of less than 0.7° over the C- and L-bands, and will be useful in a digital coherent receiver for transmission systems operating at 100 Gbit/s or more.

Keywords: 90° optical hybrid, planar lightwave circuit

Classification: Optoelectronics, Lasers and quantum electronics, Ultrafast optics, Silicon photonics, Planar lightwave circuits

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1 Introduction

Optical multilevel modulation formats using digital coherent detection are considered to be promising candidates for constructing next-generation high-capacity transmission systems. In their receiver, 90° optical hybrids are absolutely essential for retrieving in-phase and quadrature (I and Q) components from optical signals. Thus, waveguide-type 90° hybrids are now attracting considerable attention because of their potential for providing ultra-compact optical receivers [1, 2, 3]. Various kinds of 90° hybrids have been reported in waveguides made of several different materials, including silica, LiNbO₃, InP and silicon-on-insulator. Their configurations are classified into three groups; 4×4 or 2×4 multimode interference (MMI) couplers [4, 5, 6], star couplers [7], and 3-dB couplers and phase shifters [8, 9]. Of these, the 90° hybrid consisting of four 3-dB couplers and a phase shifter as shown in Fig. 1 (a) has such advantages as a low excess loss and a low loss imbalance between the four outputs. In addition, the phase difference between the I and Q components can be precisely adjusted to 90° by tuning the refractive index of a waveguide arm [10]. This phase-difference adjustability enables us to eliminate the actively controlled phase shifters. However, if we are to use 90° hybrids over a wide wavelength range without any adjustment, it is important to reduce their wavelength-dependent phase-difference deviation from 90°. In this letter, we derive the wavelength-dependent phase-difference deviation and describe our technique for reducing it. In addition, we demonstrate phase-difference deviation reduction in a silica-waveguide 90° hybrid experimentally.

2 Technique for reducing phase-difference deviation

First, we describe the reason for the phase-difference deviation in the 90° hybrid as shown in Fig. 1. Note that two input lights, which are signal

Fig. 1. Schematic configuration of 90° hybrid (a) conventional (b) this work hybrid experimentally

and local oscillator (LO) lights, are launched into inputs #2 and #4 in the conventional configuration (Fig. 1 (a)). The combination of two input ports makes a difference as regards the phase-difference deviation as we discuss later. Here, let us consider the relation between the phase-difference deviation and four output lights. The output electric field from the 90° hybrid is expressed as follows:

$$\begin{pmatrix} E_1 \\ E_2 \\ E_3 \\ E_4 \end{pmatrix} = \frac{\sqrt{P_S}}{2} \begin{pmatrix} \exp(j(\psi(t) + \pi + \Delta\theta + \Delta\phi)) \\ \exp\left(j\left(\psi(t) + \frac{3}{2}\pi + 2\Delta\theta + \Delta\phi\right)\right) \\ \exp(j\psi(t)) \\ \exp\left(j\left(\psi(t) + \frac{\pi}{2} + \Delta\theta\right)\right) \end{pmatrix} + \frac{\sqrt{P_L}}{2} \begin{pmatrix} \exp(j(\pi + 2\Delta\theta)) \\ \exp\left(j\left(\frac{\pi}{2} + \Delta\theta\right)\right) \\ \exp(j(\frac{\pi}{2} + \Delta\theta)) \\ 1 \end{pmatrix} \quad (1)$$

where $\psi(t)$ is the phase of the signal in reference to the LO light phase, $\Delta\theta$ is the phase-difference deviation from 90° between two outputs in the 3-dB coupler as shown in the inset of Fig. 1 (a), $\Delta\phi$ is the deviation of the phase shift induced by the phase shifter (a quarter wavelength delay) from 90°, P_S and P_L are the input powers of the signal and LO lights. The first and second terms on the right-hand side of Eq. (1) correspond to the outputs of the signal light from input #2 and the LO light from input #4, respectively. In general, balanced detection is preferred to single-ended detection because of the former's higher sensitivity. Output photocurrents from balanced photodetectors for I and Q components are written as follows.

$$i_I = |E_1|^2 - |E_2|^2 = R \frac{\sqrt{P_S P_L}}{2} \{ \cos(\psi(t) - \Delta\theta + \Delta\phi) + \cos(\psi(t) + \Delta\theta + \Delta\phi) \} \quad (2a)$$

$$i_Q = |E_3|^2 - |E_4|^2 = R \frac{\sqrt{P_S P_L}}{2} \{ \sin(\psi(t) - \Delta\theta) + \sin(\psi(t) + \Delta\theta) \} \quad (2b)$$

where R is the responsivity of the photodetectors. Here, we ignore the loss imbalance of the 90° hybrid and the variation in R . Assuming that the phase deviations, $\Delta\theta$ and $\Delta\phi$, are very small ($\Delta\theta \ll 1$ and $\Delta\phi \ll 1$), Eqs. (2a) and (2b) can be transformed as follows.

$$i_I = R\sqrt{P_S P_L}(\cos(\psi(t) + \Delta\phi)) \quad (3a)$$

$$i_Q = R\sqrt{P_S P_L}(\sin(\psi(t))) \quad (3b)$$

These equations indicate that $\Delta\phi$ destroys the orthogonality between the I and Q components and degrades the receiver performance. Thus, we must reduce the phase deviation $\Delta\phi$. However, ϕ inevitably has a wavelength-dependent phase deviation for the following reason. To realize orthogonality between the I and Q components, one waveguide arm is made a quarter wavelength longer, $\Delta L = \lambda_0/(4n_0)$, than the other three waveguide arms. n_0 is the refractive index for a wavelength of λ_0 . However, the phase shift $2\pi \cdot n_0 \Delta L / \lambda_0$ equals 90° only for λ_0 , because ΔL has no variability. So, the phase shift necessarily has a wavelength-dependent phase deviation $\Delta\phi$.

Next, we describe our technique for reducing the phase-difference deviation between the I and Q components. Figure 1(b) shows our proposed 90° hybrid configuration. Compared with the conventional configuration (Fig. 1(a)), the input port of the signal light is changed from #2 to #1. In this case, the output electric fields are expressed as follows.

$$\begin{pmatrix} E'_1 \\ E'_2 \\ E'_3 \\ E'_4 \end{pmatrix} = \frac{\sqrt{P_S}}{2} \begin{pmatrix} \exp\left(j\left(\psi(t) + \frac{\pi}{2} + \Delta\phi\right)\right) \\ \exp(j(\psi(t) + \pi + \Delta\theta + \Delta\phi)) \\ \exp\left(j\left(\psi(t) + \frac{\pi}{2} + \Delta\theta\right)\right) \\ \exp(j(\psi(t) + \pi + 2\Delta\theta)) \end{pmatrix} + \frac{\sqrt{P_L}}{2} \begin{pmatrix} \exp(j(\pi + 2\Delta\theta)) \\ \exp\left(j\left(\frac{\pi}{2} + \Delta\theta\right)\right) \\ \exp\left(j\left(\frac{\pi}{2} + \Delta\theta\right)\right) \\ 1 \end{pmatrix} \quad (4)$$

In a similar procedure for the conventional configuration described above, the output photocurrents for the I and Q components are written as follows.

$$\begin{aligned} i'_I &= |E'_1|^2 - |E'_2|^2 = R \frac{\sqrt{P_S P_L}}{2} \{ \sin(\psi(t) - 2\Delta\theta + \Delta\phi) + \sin(\psi(t) + \Delta\phi) \} \\ &= R\sqrt{P_S P_L}(\sin(\psi(t) + \Delta\theta - (2\Delta\theta - \Delta\phi))) \end{aligned} \quad (5a)$$

$$\begin{aligned} i'_Q &= |E'_3|^2 - |E'_4|^2 = R \frac{\sqrt{P_S P_L}}{2} \{ \cos(\psi(t)) + \cos(\psi(t) + 2\Delta\theta) \} \\ &= R\sqrt{P_S P_L}(\cos(\psi(t) + \Delta\theta)) \end{aligned} \quad (5b)$$

Since $\Delta\theta$ is common to i_I and i_Q , this phase deviation can be corrected by employing carrier phase recovery during digital signal processing [11]. ($2\Delta\theta$

$-\Delta\phi$) destroys the orthogonality for the 90° hybrid as shown in Fig. 1 (b). Compared with Eqs. (3a) and (3b), Eqs. (5a) and (5b) mean that if we achieve $|2\Delta\theta - \Delta\phi| < |\Delta\phi|$, the phase-difference deviation between the I and Q components can be reduced solely by changing the input port of one 3-dB coupler. That is, we can reduce the phase-difference deviation by compensating for the deviation of the phase shift, $\Delta\phi$, with the phase-difference deviation in 3-dB couplers, $\Delta\theta$. For the silica-based planar lightwave circuit (PLC) with a refractive index difference between the core and cladding of 1.5% that we adopted in our experiment described below, we estimated the wavelength dependence of $\Delta\theta$ and $\Delta\phi$ to be -0.021 and -0.045 [$^\circ/\text{nm}$], respectively, using a first-order approximation. Therefore, we expect the phase-difference deviation to be reduced by canceling $2\Delta\theta$ and $\Delta\phi$ in our proposed 90° hybrid configuration. Note that we have to use a 2×2 MMI coupler instead of a directional coupler as the 3-dB coupler, because the phase difference of the two outputs in the directional coupler is always 90° regardless of the wavelength ($\Delta\theta = 0$), and changing the input port has no effect.

3 Experimental results

To confirm the phase-difference deviation reduction with our proposed technique experimentally, we fabricated 90° hybrid samples using silica-based PLC technology. The refractive index difference was 1.5%, and the waveguide core size was $4.5 \times 4.5 \mu\text{m}^2$. ΔL was set at $0.27 \mu\text{m}$ for a λ_0 of $1.57 \mu\text{m}$. To measure the phase difference between the outputs, we installed a 1×2 coupler and a delay line so that the circuit worked as a 1×4 delay interferometer as shown in Fig. 2 (a). The free spectral range of the delay interferometer was 125 GHz.

We measured the transmission spectra of the fabricated delay interferometers. Figure 2 (b) shows the measured transmission spectra as an example. We then calculated the power difference between outputs #1 and #2 (Eq. (3a) or (5a)) and #3 and #4 (Eq. (3b) or (5b)) as shown in Fig. 2 (c), and estimated the phase differences between two power difference curves. Figure 3 shows the measured phase difference for 90° hybrids fabricated with the conventional configuration and our proposed configuration. While the phase-difference deviation from 90° was less than 2.3° for the conventional configuration, our proposed 90° hybrid had a phase-difference deviation of less than 0.7° over the C- and L-bands. These experimental results indicate that our proposed technique worked as intended.

4 Conclusion

We demonstrated a silica-waveguide 90° hybrid with a very low phase-difference deviation from 90° of less than 0.7° that we achieved solely by selecting the proper input ports in the 3-dB coupler. Our 90° hybrid can be used for both the C- and L-bands without any active controls. We believe our 90° hybrid will contribute to providing a cost-effective digital coherent receiver for transmission systems operating at 100 Gbit/s or more.

Fig. 2. (a) Schematic configuration of fabricated samples (b) measured transmission spectra (c) output power difference

Fig. 3. Measured phase difference between I and Q components (a) conventional (b) this work

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