Compact and wideband optical 90º hybrid based on a one-way tapered MMI coupler

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Abstract: We report compact and wideband 90º hybrid with a one-way tapered 4×4 MMI waveguide. The fabricated device with a device length of 198 μm exhibited a phase deviation of <±5.4º over a 70-nm-wide spectral range.

OCIS codes: (130.3120) Integrated optics devices; (230.7370) Waveguides

1. Introduction

To date, many research institutes have reported several kinds of waveguide-based optical 90º hybrids that are compatible with monolithic integration to photodiodes [1-3]. Among several kinds of waveguide-based 90º hybrids, a 4×4 multimode interference (MMI) coupler has been actively investigated as a promising candidate due to its compactness and structural simplicity [2]. As a matter of course, further size reduction of the 4×4 MMI coupler will be more favorable to large-scale monolithic integration. The size of the 4×4 MMI coupler can be readily decreased by reducing the MMI width [4]. However, it should be noted that a proximity effect that inherently takes place during a fabrication process normally determines the narrowest gap between waveguide arrays (*Gap*) of the 4×4 MMI coupler. To overcome this limitation, D. S. Levy *et al* reported a butterfly shaped parabolic-tapered MMI structure that minimizes excessive phase differences among the self-images formed at the MMI region's mid-plane [5]. Unfortunately, when the butterfly shaped parabolic-tapered MMI coupler is applied to an optical 90º hybrid, an operating bandwidth are normally reduced as the dimension of the MMI region is decreased.

In this work, we propose a new-type optical 90º hybrid where the 4×4 MMI region is one-way linear-tapered along the propagation direction, and theoretically and experimentally verify its superior performances to the conventional parabolic-tapered 4×4 MMI coupler from the viewpoint of compactness and a broad bandwidth. We experimentally demonstrate a quadrature phase behavior with a low wavelength sensitive loss of <1.4dB and a low phase deviation of <±5.4º over a 70-nm-wide spectral range.

2. Device structure

Figure 1 shows a schematic diagram of the proposed 90º hybrid based on a one-way tapered MMI region. As shown in Fig. 1, a basic idea is that the initial MMI width (W_{MS}) can be narrower than the output MMI width (W_{MF}), because an optical 90º hybrid normally requires only two input channels for a signal and a local oscillator (LO). It is important to note that these two input channels are asymmetrically positioned for realizing quadrature phase relation. If we subtract any constant phase offset in the MMI region, the output phase relation of the device shown in Fig. 1 is given by S+L for Ch-1, S+jL for Ch-2, S–jL for Ch-3 and S–L for Ch-4, respectively.

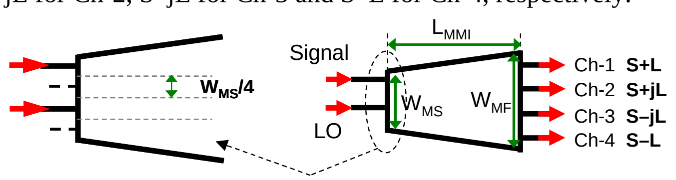

Fig. 1. Schematic diagram of the proposed optical 90º hybrid based on a one-way linear-tapered MMI waveguide

Usually, an optical 90º hybrid is required to have not only quadrature phase relation but also well-balanced splitting ratio for all output channels. Figure 2 shows the calculated transmission spectra (left side) and their relative phase deviation (Δφ) from the quadrature phase relation (right side) for the parabolic-tapered 4×4 MMI coupler with *Gap*=2.3 μm (a) and *Gap*=1.0 μm (b) and for the proposed device with *Gap*=2.3 μm (c) and *Gap*=1.0 μm (d). In the FD-BPM simulation, we assumed a deep-ridge optical waveguide structure with a GaInAsP/InP material system. The access waveguide width (W_{acs}) was commonly set to 2.0 μm. The MMI length (L_{MMI}) was optimized for the wavelength of 1.55 μm (λ_0) [4,5].

In Fig. 2(a), the middle MMI width (W_{MM}) was set to 13.2 μm (W_{MF}–W_{MM}=4 μm), which makes L_{MMI} ~30% shorter (=436 μm) as compared with that of the rectangular-shaped MMI with the same W_{MF} (=622 μm) [5]. In this case, even if the transmittances and Δφ for each output channel are balanced at around λ_0 due to the minimized excessive phase errors among the self-images at the parabolic-tapered MMI region, an operating bandwidth is limited to be 17 nm. Additionally, it was theoretically verified that as shown in Fig. 2(b), the quadrature phase relation in the parabolic-tapered MMI is markedly degraded in inverse proportion to the value of *Gap*. In this case, W_{MM} was set to 9.0 µm (W_{MF}–W_{MM}=3 µm), which makes L_{MMI} ~31% shorter (=207 µm) as compared with that of the rectangular-shaped MMI (=298 µm). As clearly shown in Fig. 2(b), although spectral wavelength sensitivity was somewhat relaxed, the available spectral range vanished away, which is most likely due to the degraded self-imaging quality in the MMI region.

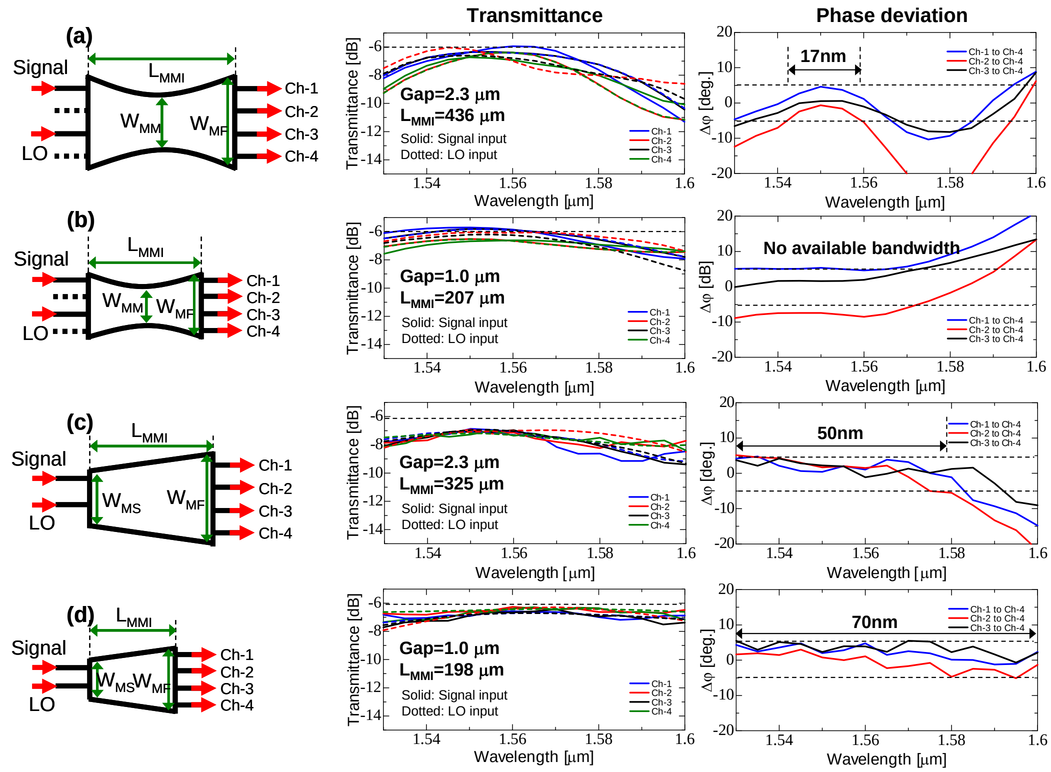

Fig. 2. Calculated transmittance and phase deviation (Δφ) for the parabolic-tapered 4×4 MMI coupler with (a) *Gap*=2.3 µm and (b) *Gap*=1.0 µm, and for the proposed device with (c) *Gap*=2.3 µm and (d) *Gap*=1.0 µm

Unlike the case of the parabolic-tapered 4×4 MMI coupler, since the MMI taper variation of the proposed scheme shown in Fig. 1 stays constant, the degradation of interchannel balance and bandwidth becomes less sensitive to the excessive phase errors among the self-images at the linear-tapered MMI region, which makes it easier to further reduce the required L_{MMI} for arbitrary MMI parameters such as W_{MS}, W_{MF} and *Gap* etc. In Fig. 2(c), W_{MS} was set to 9.2 µm (W_{MF}–W_{MS}=8 µm), which makes L_{MMI} ~48% shorter (=325 µm) as compared with that of the rectangular-shaped MMI (=622 µm). Although L_{MMI} is much shorter, an interchannel balance is much better than the case shown in Fig. 2(a), preserving a low phase deviation of Δφ<±5.0º over a 50-nm-wide spectral range. These superiorities of the proposed scheme were still available when *Gap* was set to 1.0 µm as depicted in Fig. 2(d). In this case, W_{MS} and W_{MF} were set to be 8.0 µm and 12.0 µm. As a result, L_{MMI} was reduced to 198 µm, which is ~34% shorter than that of the rectangular-shaped MMI (=298 µm). As can be clearly seen in Fig. 2(d), the proposed device exhibited not only less spectral wavelength sensitivity but also markedly increased available bandwidth (Δφ<±5.0º) of more than 70 nm, which explains the proposed scheme would be very promising for achieving both compactness and a broad bandwidth without being limited by any arbitrary MMI parameters.

3. Experimental

Based on the calculation results, the proposed devices were fabricated on InP wafers with a 0.3-µm-thick GaInAsP core layer (bandgap wavelength λ_g=1.3 µm). Figure 3 shows a top-view of the proposed 90º hybrid with *Gap*=1.0 µm. In this experiment, to measure the phase behavior of the fabricated device, a delayed interferometer whose free-spectral range was designed to ~530 GHz was directly coupled to the device. Then, the transmission spectra of the fabricated device were measured for a linearly polarized TE mode.

Figure 4 shows the measured transmission spectra of the fabricated device with *Gap*=1.0 μm (see Fig. 3). Each output transmittance sinusoidally changed in accordance with the phase differences at the delayed interferometers. Also, π-phase deviations were clearly observed at the In-phase channels (Ch-1 and 4) and the Quadrature channels (Ch-2 and 3). The spectrum envelopes correspond to the transmittances of the device. In this case, a wavelength sensitive loss was measured to be <1.4dB over a 70-nm-wide spectral range (see Fig. 4).

Figure 5 shows the measured Δφ of the fabricated device. As can be seen in Fig. 5, we experimentally verified that a quadrature phase relation of the proposed device can be kept nearly constant over a broad spectral range. Δφ for each output channel was experimentally estimated to be <±5.4° over a 70-nm-wide spectral range. These experimental results were comparable with the numerical simulations shown in Fig. 2(d).

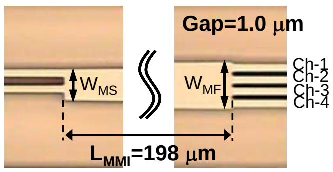

Fig.3. Fabricated optical 90° hybrids with *Gap*=1.0 μm

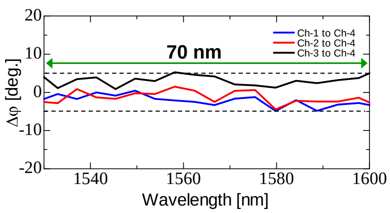

Fig. 5. Measured Δφ of the fabricated device

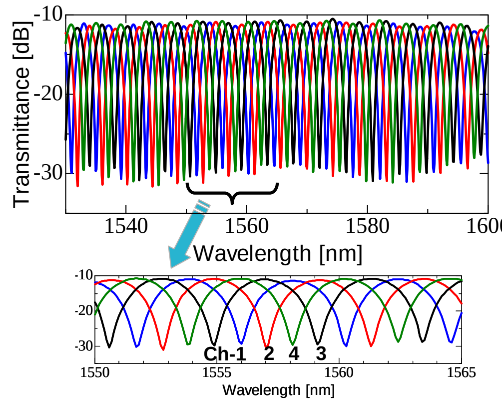

Fig. 4. Measured transmission spectra of the fabricated device

As shown in Table I, the proposed 90° hybrid based on the one-way linear-tapered 4×4 MMI requires to have some of output waveguide arrays intersected for performing balanced detection [1]. Although no crossover is required in our previous compact 90° hybrid with linear-tapered 2×4 MMI and 2×2 MMI couplers [6], it is accompanied by the reduction of operating bandwidth (<40 nm) due mainly to the phase matching relation between the two MMI components. Overall, the proposed 90° hybrid could be very attractive for achieving both compact device size and a broad bandwidth.

Table I. Comparison of device length, bandwidth and need for waveguide crossover for our two kinds of optical 90° hybrids

	This work	Previous work in Ref. 6
Device length	198 μm	227 μm
Operating bandwidth	70 nm	40 nm
Crossover for balanced detection	Required	Unnecessary

4. Summary

We demonstrated a novel optical 90° hybrid based on a one-way linear-tapered 4×4 MMI coupler. It was theoretically and experimentally verified that the proposed 90° hybrid not only shows a broad operating bandwidth, but also serves to reduce substantially the device length by a factor of 1.5~1.9. The fabricated device with an InP-based deep-ridge waveguide exhibited clear quadrature phase response (|Δφ|<5.4°) over a 70-nm-wide spectral range.

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