

Wavelength- and Polarization-Insensitive Integrated Directional Couplers using Mach-Zehnder Structures

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INTRODUCTION

Directional couplers are essential components in a wide variety of important devices, including modulators, switches, and Bragg-grating add/drop filters [1,2]. For many of these applications, it is important that the directional coupler provide the desired power splitting ratio, independent of wavelength or polarization. Broadband performance is especially important in wavelength division multiplexing systems, where a constant splitting ratio must be maintained for all wavelength channels. Using conventional couplers, it is often impossible to achieve broadband polarization-insensitive performance, especially in planar integrated devices.

In this work we describe the design, fabrication, and measurement of a class of integrated directional couplers which provide wavelength-, polarization-, and fabrication-insensitive performance.

Others have recognized that wavelength-insensitive couplers can be realized by cascading two conventional couplers in a Mach-Zehnder configuration [3,4]. Using numerical optimization techniques in combination with empirically determined wavelength-dependence data, researchers at NTT have employed this technique to build broadband 20% couplers [3].

In contrast, this paper offers simple, analytical design rules for building such cascaded couplers with arbitrary splitting ratios. We apply these rules to the particularly important case where 50% splitting is required [1,2]. By directly comparing the performance to that of a similarly-constructed conventional coupler, we demonstrate that these simple analytical design rules yield devices which are not only wavelength-insensitive, but also polarization-insensitive and fabrication-insensitive. Specifically, our couplers achieve near-50% power splitting over a 120 nm bandwidth, for both polarizations. Furthermore, our measurements indicate that the devices are robust to fabrication deviations and material uncertainties.

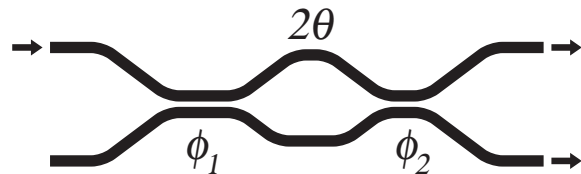


Fig. 1. Structure of the parameter-insensitive coupler: two non-identical conventional couplers separated by a relative phase shift 2θ .

DESIGN

The structure of the insensitive coupler is depicted schematically in Fig. 1. The device consists of two conventional directional couplers, cascaded in a Mach-Zehnder configuration, with a relative phase shift introduced between them. The device achieves insensitive performance in the following manner: a fractional change in wavelength (or polarization, refractive index, waveguide size, etc.) tends to affect each directional coupler in the same way. The relative phase shift between the two couplers causes these deviations to balance each other such that the resulting power splitting ratio remains unchanged.

The splitting ratio at the output of the device can be expressed in terms of three dimensionless quantities, ϕ_1 , ϕ_2 , and 2θ [3,5]:

$$S = \cos^2 \theta \sin^2(\phi_1 + \phi_2) + \sin^2 \theta \sin^2(\phi_1 - \phi_2). \quad (1)$$

ϕ_1 and ϕ_2 represent, respectively, the total integrated coupling of the two constituent directional couplers, and 2θ is the relative phase shift which separates them. Each of these parameters depends implicitly upon wavelength, polarization, etc.. As we describe in a previous work [5], insensitive performance is achieved by choosing these three

parameters in the following way:

$$\phi_1 = \frac{3\pi}{8} \left(1 + \frac{1}{N}\right), \quad \phi_2 = \frac{3\pi}{8} \left(1 - \frac{1}{N}\right) \quad (2)$$

$$\cos^2 \theta = \sin \left(\frac{3\pi}{2N}\right) \left[N + \sin \left(\frac{3\pi}{2N}\right)\right]^{-1} \quad (3)$$

where N is a dimensionless real parameter larger than 3. N can be chosen to give any desired splitting ratio as described in (1). In the case where 50% splitting is required, $N = 3$ and the solutions are particularly simple: $\phi_1 = \pi/2$, $\phi_2 = \pi/4$, and $\theta = \pi/3$.

Knowing the three quantities ϕ_1 , ϕ_2 , and 2θ , we then designed a waveguide device to nominally achieve the desired accumulated coupling factors and phase shift. We began by selecting a suitable waveguide geometry and material system. Based upon vendor-supplied information about the refractive indices at $\lambda = 1.55 \mu\text{m}$, we designed waveguide geometry to yield efficient coupling to an optical fiber. Using coupled mode theory, we calculated the waveguide coupling as a function of separation, and with this information we designed the two directional couplers. The phase shift 2θ is achieved by making one arm of the interferometer slightly longer than the other. For all calculations, we used a free-space wavelength of $1.55 \mu\text{m}$. Fig. 2 illustrates the important design parameters.

FABRICATION

It is important to point out that we did not include a range of coupling lengths (ϕ_1 and ϕ_2), waveguide separations, or waveguide widths on our optical mask. Instead, we used only our best estimate for these parameters based upon the calculations described above. After all, the purpose of the device is to compensate for any deviations from the nominal design. However, we did include a range of phase shifts (θ) above and below the nominal design. The optical photomask was written with e-beam lithography, using a relatively coarse (and therefore economical) pixel size of $0.12 \mu\text{m}$. The patterns were carefully placed to insure that each device does not cross an e-beam field boundary, which could introduce spurious phase shifts. For comparison, we included in our design a set of conventional directional couplers, designed to achieve 50% splitting ratios at $\lambda = 1.55 \mu\text{m}$.

The device is fabricated using commercially available Ge doped SiO_2 planar waveguides, with a core to clad refractive index contrast of 0.3%. Initially, a $1 \mu\text{m}$ -thick silicon layer is sputter-deposited over the substrate. We then use deep UV optical contact photolithography to transfer the waveguide patterns from a mask to the substrate. The

silicon layer is patterned by reactive ion etching in Cl_2 . The waveguides are then etched to a depth of $6.8 \mu\text{m}$ by reactive-ion etching in CHF_3 , using the silicon layer as a hard mask. A final layer of cladding is then deposited over the structure.

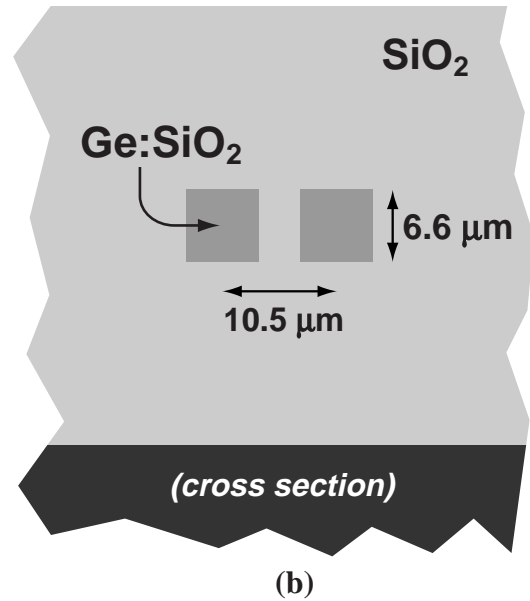
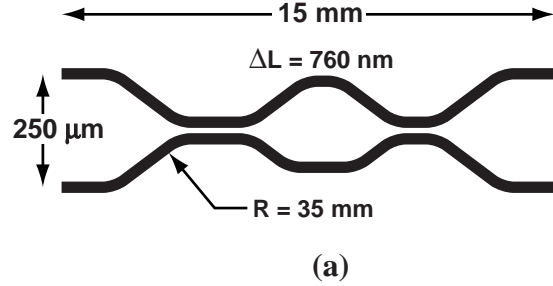


Fig. 2. (a) Diagram (not drawn to scale) of the cascaded direction couplers, indicating important dimensions. (b) Cross-sectional diagram illustrating waveguide geometry at point of closest separation.

MEASUREMENT

To prepare the samples for measurement, we polished the input facet normal to the waveguides to allow butt-coupling from a cleaved fiber. We polished the output facet at 10 degrees from the normal to prevent unwanted reflections. We measured the performance of the couplers using an external cavity tunable diode laser. Light from the laser was sent into one port of the device through a single-mode fiber, using an index-matching gel to improve the coupling efficiency. At the output facet, the light

emerging from either waveguide was separately imaged onto a power meter.

For a representative device, the total insertion loss (including fiber-coupling loss, bending loss, and intrinsic waveguide loss) was approximately 1.0 dB.

Fig. 3 plots the splitting ratio vs. wavelength for a conventional directional coupler and for an improved insensitive coupler. Notice that the conventional coupler achieves a splitting ratio which is uniformly higher than the nominal value of 50%. We attribute this discrepancy to (i) uncertainty in the material indices of refraction used in our calculations, and (ii) structural and material deviations from the nominal design which may occur during the various fabrication steps. In principle, this bias can be removed by performing a more exhaustive empirical investigation of the material properties and by carefully controlling and characterizing each step of the fabrication process. However, in addition to this offset, the conventional coupler exhibits a sloped wavelength dependence which is characteristic of directional couplers and cannot be flattened without using a completely different design.

The conventional coupler also exhibits significant polarization dependence: the splitting ratio is consistently higher for TM- than for TE-polarized light at all of the wavelengths measured. We attribute this difference to material birefringence in the deposited oxide films.

In spite of this polarization dependence, and the apparent uncertainty in material and fabrication parameters, the cascaded Mach-Zehnder coupler achieves a splitting ratio between 45 and 50% (within 5% of the targeted value) over the entire wavelength range from 1475 – 1595 nm (spanning 120 nm), with negligible polarization dependence.

CONCLUSIONS

Based upon simple design rules, we have constructed a set of cascaded Mach-Zehnder couplers which are insensitive to wavelength, polarization, and other material and structural parameters. In spite of relatively large uncertainties in the materials and fabrication, these devices show remarkably low wavelength and polarization dependence. By more carefully controlling and characterizing the materials and fabrication, we believe that we can bring these devices closer to the nominal design, which should further improve their performance.

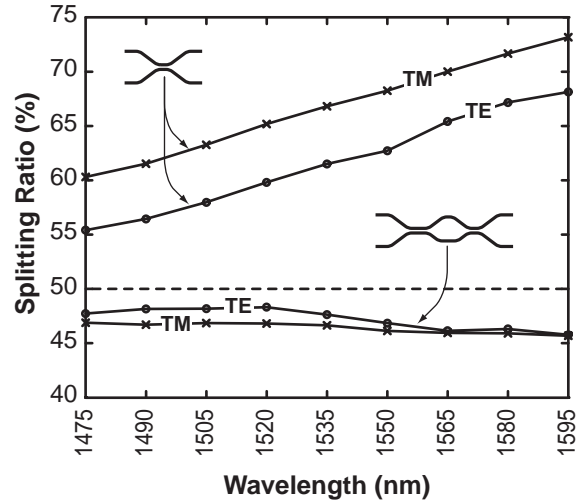


Fig. 3. Measured power splitting ratio vs. wavelength for two devices: the upper two curves represent the measured splitting ratio for a conventional coupler (TE and TM polarizations), and the lower two curves correspond to the parameter-insensitive Mach-Zehnder coupler.

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