Tolerant, Broadband Tunable 2×2 Coupler Circuit

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***Abstract*—We designed and demonstrated a coupler circuit with tunability for arbitrary coupling ratio and being tolerant to process errors. We also demonstrate that the circuit can be tuned to a uniform coupling spectrum over a 50 nm spectral bandwidth.**

***Index Terms*—tunable coupler, broadband coupler, programmable photonics**

I. Introduction

In programmable photonic circuits [1], one of the essential building blocks is a tunable optical 2×2 coupler, that can change its coupling ratio from 0% to 100%, and preferably over a wide wavelength range. This is essential for linear transformations, switch fabrics or bandpass filters. To implement a static 2×2 coupler, the directional coupler (DC) is one of the simplest coupling structures. However, a DC implemented in silicon is very sensitive to process variations, and therefore difficult to make with an exact coupling ratio. Also, DCs usually have a very dispersive spectral response and cannot be tuned over a wide range. A common way of implementing a tunable 2×2 coupler is a balanced Mach-Zehnder interferometer (MZI). The MZI is constructed from two static 50:50 couplers (e.g. DCs), connected with two delay lines with integrated phase shifters (e.g. heaters). The coupling response of the MZI can be swept from minimum to maximum by tuning the phase delay from 0 to π. However, to obtain the full 0-100% coupling range, the two static couplers need to have a perfect 50:50 splitting balance, which is not easy to design over a wide wavelength range. In [2], it is suggested to replace the two couplers each with a 2×2 MZI coupler that can be tuned to a 50:50 ratio as long as the balance of the DCs is better than 15:85. Indeed, such a three-stage MZI enables a full tuning range, but requires at least 3 phase shifters to configure. In this paper, we simplify this concept and show that we can achieve similar performance with a two-stage MZI, as shown in Fig. 1, in a similar was as presented in [3]. This eases the control and lowers the power consumption, as we only need two phase shifters. We also show that this circuit can be tuned for a uniform coupling over a wide bandwidth of 50 nm, making it easier to construct wavelength filters or route broadband light through a programmable circuit [4].

II. Two-stage MZI 2×2 Tunable Coupler

The design of the two-stage is depicted in Fig. 1a. The circuit connects three DCs with two sets of balanced delay lines with phase shifters. In our fabricated device we incorporated phase shifters in all arms of the circuit, so we have 4 phase shifters, but in practice it is possible to use only two. We can adjust the transmission by tuning the phase shift in the two stages. Compared to the three-stage design, the tuning algorithm becomes simpler and covers only a two-dimensional space $[\Delta\varphi_1, \Delta\varphi_2]$. The device can be tuned from 0% to 100% as long as the three directional couplers have a balance that is better than 25:75. This makes the circuit tolerant to fabrication imperfections and even local variability, as it is not required that all three DCs perform identically.

We fabricated our design on the IMEC iSiPP50G silicon photonics platform. Due to an unfortunate design error, we used the wrong length of the directional coupler, which means that they have a coupling strength that is way below 25% at our target wavelength of 1550 nm. However, for longer wavelengths, we find that the coupling increases, up to 27% at 1610 nm. While this is at the edge of the measurement range, it allows us to validate the operational principle of this circuit: Fig 2a shows the simulated circuit transmission in the $[\Delta\varphi_1, \Delta\varphi_2]$ control space assuming 27% coupling for the DCs. Fig. 2b shows the measured transmission when controlling the tuning power of the heaters, for a wavelength of 1610 nm. We noticed a very good agreement between simulation and measurement.

III. Tuning for Broadband Operation

The tunable coupler can be operated to achieve any coupling ratio for a single wavelength. However, the directional couplers are dispersive, so we can expect that the coupling response

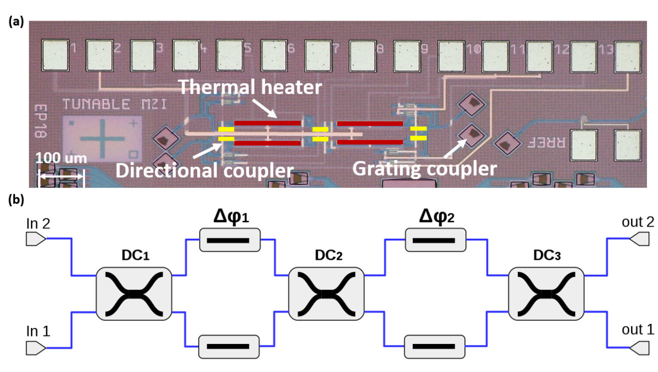

Fig. 1. (a) Microscope picture of the fabricated device.(b) Two-Stage MZI 2×2 tunable coupler.

This work has received funding from the European Research Council through grant agreement No 725555 (PhotonicSWARM).

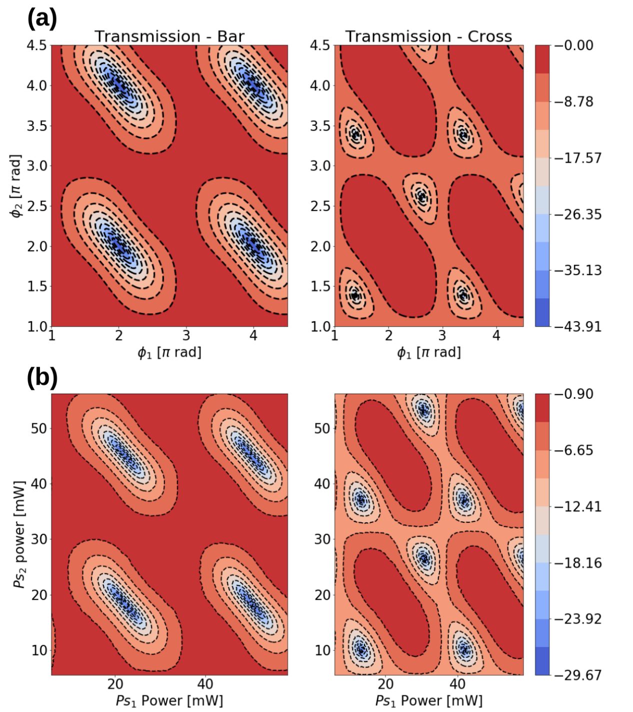

Fig. 2. (a) Simulated result for the two-stage MZI 2 × 2 tunable coupler with power coupling ratio of 27% at 1.61 μm. Power transmission is shown in logarithmic scale. (b) Measured transmission of the fabricated device. We have a strong qualitative agreement between simulation and experiment.

of the circuit can also change with wavelength. Yet it turns out that we can use the degrees of freedom of the cascade to compensate for the dispersion of the DCs. Tran et al. [5]

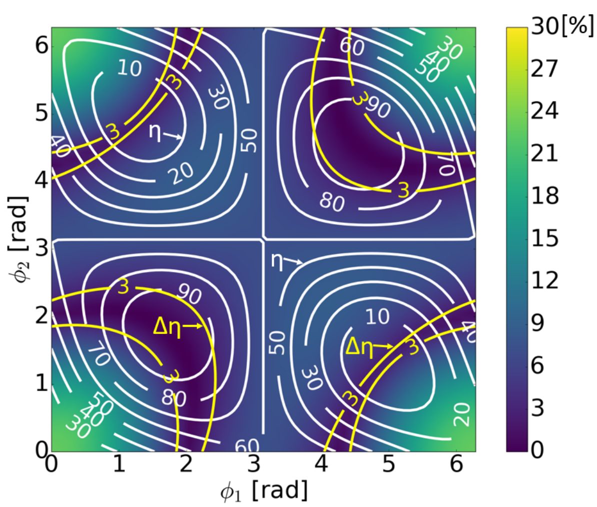

Fig. 3. Simulated result of cross transmission η at 1550 nm and the maximum deviation of the cross coupling $\Delta\eta$ from 1525 to 1575 nm for the two-stage tunable coupler with imperfect DCs of 40:60 coupling ratio. The dark lines in the graph indicate the region of 3% deviation from the desired coupling within a 50 nm wavelength range of 1550 nm. As this region contains all coupling values from 0-100%, we can tune the circuit to a 50 nm broadband coupling regime with a tolerance of 3%.

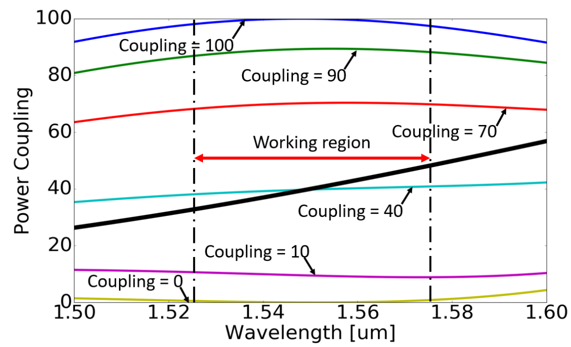

Fig. 4. The simulated cross power transmission for 0%,10%,40%,70% 90% and 100% coupling ratio.Within the working region between 1525 nm and 1575 nm indicated by the dashed line, the device works as a broadband coupler with a deviation less than 3%. Outside this working region, the coupler suffers more wavelength dispersion. The dispersive response of a single DC with 40:60 coupling ratio at 1550 nm is also shown by black bold line.

proposed a single stage MZI that has a flat response over 50 nm range, but with a tuning range limited to 10-70%. Using the circuit in Fig.1, we can achieve broadband operation for any arbitrary coupling ratio. As our fabricated circuit is already on the edge of our measurement range, we currently can only validate this in simulation. We assume the circuit consists of imperfect DCs of 40:60 coupling ratio at 1550nm. In Fig. 3, we plot the power coupling η at 1550 nm (white contours), and overlay it with the maximum deviation $\Delta\eta$ within the wavelength range of 1525-1575 nm. For any given desired coupling value, we can tune the two phase shifters such that we obtain this coupling value within 3% over the entire wavelength range for an almost uniform response. Figure 4 shows the simulated cross power transmission for the best operating point for coupling values of 0%,10%,40%,70%,90% and 100%. The maximum dispersion of coupling power is 3% between 1525 nm and 1575 nm.

IV. Conclusion

We designed and demonstrated a simplified tunable coupler circuit with 0-100% coupling range even under conditions of fabrication variations. We also show that we can bias the circuit to obtain a flat spectral response over a wavelength range of 50 nm.

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