Tunable multimode interference coupler

D.A. May-Arrioja, P. LiKamWa, C. Velásquez-Ordóñez and J.J. Sánchez-Mondragón

An electrically tunable multimode interference (MMI) coupler/splitter is demonstrated. The device operates by modifying the phase of the multiple self-images that are formed around the midpoint of the MMI structure. This provides a simple way to fine-tune the 50:50 output power split ratio or other arbitrary ratio.

Introduction: Multimode interference (MMI) couplers have been widely used in integrated photonic devices because of their compact size, wide optical bandwidth, polarisation independence and relaxed fabrication tolerances [1]. In most applications they operate as passive components, and only recently has their use as active components for the development of photonic switches been investigated [2, 3]. Switching is achieved by modifying the phase of the multiple self-images that occur at different lengths along the MMI waveguide. Modifying the phase relation between the self-images leads to a modified output image, and light can then be directed to a specific output waveguide. The approach works properly as long as the refractive index change is entirely confined within the areas containing the principal self-images. However, owing to the amount of refractive index change required, the devices are intended to operate by electric current injection. In this case, current spreading becomes a serious issue since the phase change is applied to a bigger area than the one delineated by the electrical contact, and thus deteriorates the optimum device performance. This has been a key factor in experimentally demonstrating such MMI devices.

In this Letter, we report the application of an area selective zinc in-diffusion process to selectively define p–n junctions across a semiconductor wafer. The isolated junction acts as a channel for the injected electrical current, and thus current spreading can be regulated by simply changing the zinc depth. Using this process we demonstrate a tunable 3 dB MMI coupler that can be easily tuned from a 90:10 to a 30:70 splitting ratio. To our knowledge, this amount of tuning has never been demonstrated before in MMI structures, and demonstrates the potential of the technique for more sophisticated MMI-based devices.

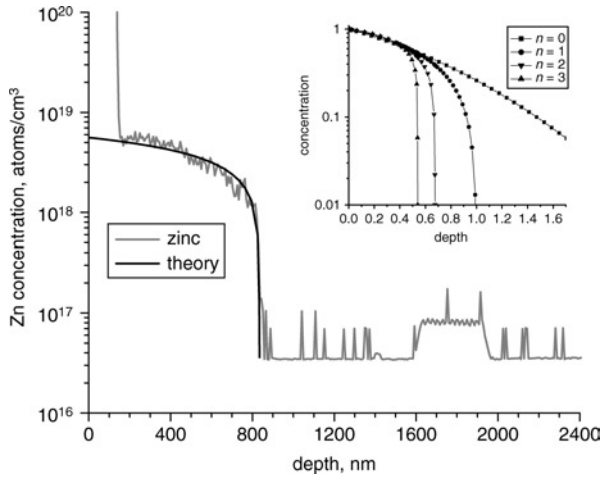

Fig. 1 *Experimental zinc diffusion profile and theoretical fitting ($n = 2$) for 30 min diffusion at 500°C*

Inset: zinc diffusion profiles for different powers of diffusion coefficient

Zinc in-diffusion in InP: It is generally accepted that the diffusion mechanism of zinc in InP is governed by an interstitial-substitutional mechanism. This diffusion mechanism can be modelled by a one-dimensional diffusion equation with a concentration-dependent diffusion coefficient [4]:

$$\frac{\partial C_s}{\partial t} = \frac{\partial}{\partial x}\left(D_{eff}\frac{\partial C_s}{\partial x}\right) \tag{1}$$

where C_s is the concentration of substitutional ions, and D_{eff} is the concentration dependent diffusion coefficient given by $D_{eff} = D_0 C_s^n$, with D_0 being a diffusion constant. The equation can be solved for the case of constant surface concentration and a semi-infinite medium. Shown in Fig. 1 (inset) are the normalised diffusion profiles obtained from (1) for the cases of $n = 0,1,2$, and 3 (depth axis normalised to $n = 1$). The case of $n = 0$ corresponds to the typical complementary error function solution that is obtained for a constant diffusion coefficient. The main feature in the inset of Fig. 1 is that a sharper diffusion front is obtained as the order n is increased, which is ideal for minimising free-carrier absorption. Interestingly, the order n of the concentration-dependent diffusion coefficient is highly dependent on the initial background donor concentration of the wafer. Highly n-type doped InP wafers ($\sim 1 \times 10^{18}$ cm^{-3}) typically exhibit a cubic dependence of the diffusion constant ($n = 3$), whereas undoped wafers ($\sim 1 \times 10^{15}$ cm^{-3}) exhibit a linear dependence ($n = 1$) [5]. Intermediate doping concentration of the order of 1×10^{17} should reveal a quadratic dependence ($n = 2$) [4]. This allows a simple way of controlling the required diffusion front.

The wafer structure used in this work consisted of an n–i–n structure similar to the one used in [6]. The n-doped InP layers were grown with a doping concentration of 2×10^{17} cm^{-3}, which should provide an $n = 2$ dependence of the diffusion profile. The zinc in-diffusion process was performed using a semi-sealed open-tube technique, which is also explained in [6]. The experimental zinc diffusion profile at 500°C for a duration of 30 min is shown in Fig. 1. A zinc depth of 0.8 μm with a sharp diffusion front was obtained for this diffusion time. Also shown in Fig. 1 is the theoretical diffusion profile for $n = 2$, which fits very well the experimental profile. We should highlight that the zinc depth can be easily modified by simply changing the diffusion time, while keeping the remaining parameters constant.

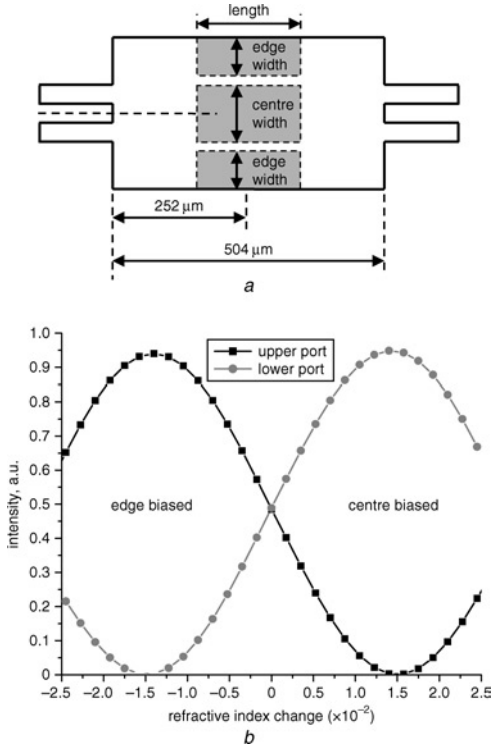

Fig. 2 *Schematic of tunable MMI coupler and design parameters, and tuning of MMI coupler against induced refractive index change*

a Schematic of MMI coupler
b Tuning of MMI coupler

Tunable MMI coupler design: The design parameters of the tunable MMI coupler are shown in Fig. 2*a*. The multimode waveguide section has a width of $W = 18$ μm and a length of $L = 504$ μm. Light is launched and extracted from the device using 3 μm-wide input and output waveguides that are separated by 3 μm. As shown in Fig. 2*a*, the shaded areas at the centre of the MMI corresponds to the index modulated regions (i.e. electrodes). The location of these zones corresponds to the areas where four multiple self-images are formed. Without any index modulation, the MMI coupler should act as a 3 dB splitter. However, by properly modifying the phase in these index modulated areas, the light can be redirected to either output waveguide and thus tune the splitting ratio. The optimum dimensions

of the index modulated areas were calculated using the finite-difference beam propagation method (FD-BPM). In this case, a maximum refractive index change of $\Delta n/n = 0.5\%$ was assumed as a result of current injection. This resulted in an electrode length of 65 μm with a centre electrode width of 8 μm and edge electrodes widths of 4 μm. The response of the device as a function of the induced refractive index change is shown in Fig. 2*b*. As can be observed, the splitting ratio can be easily tuned by reducing the refractive index through either the centre or the edge electrodes. In both cases, full switching is achieved when a phase change of $\pi/2$ is induced.

Experimental results: The device was fabricated by first depositing a 200 nm-thick silicon nitride (Si_3N_4) film that is used as a diffusion barrier for the zinc in-diffusion process. Photolithography and dry etching were then used to open windows for the index modulated areas. The zinc in-diffusion process was then performed. After the diffusion, Ti/Zn/Au *p*-type contacts are patterned on the zinc diffused areas using lift-off. The MMI structure was then patterned by photolithography, followed by selective wet chemical etching. The wafer substrate was then lapped to a thickness of 150 μm and polished to a mirror finish. The *n*-type contact (Ni/Ge/Au) was then deposited by thermal evaporation and annealed-in. The sample was cleaved and mounted on a copper holder for device testing.

The normalised output intensity against applied current characteristics of the device for a 1560 nm wavelength is shown in Fig. 3. It can be seen that, with no current applied, the splitting ratio is not exactly 50:50. However, this can be tuned by injecting current into the patterned electrodes. When the edge electrodes are biased, the splitting ratio can be easily switched to better than a 90:10 splitting ratio. Note also that, during the first 3 mA of current injection, the splitting ratio is not modified. We believe that this is caused by a modification of the imaging due to strain induced by the Si_3N_4 and metal contacts, which reduces the overlap between the self-images and the electrodes. However, as evidenced in Fig. 3, the injection of a small current of only 0.7 mA through the centre electrode is required to trim the device for an exact 50:50 split of the output powers. By increasing the applied current, the splitting ratio can be changed to a 30:70 split ratio in the other direction. Beyond this point the behaviour deviates significantly from the theoretically expected response. We believe that the injected electrons have spread too far beyond the optimum region for index modulation and therefore the device stops working as expected.

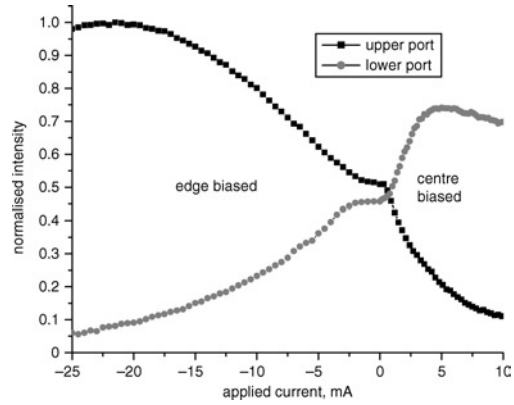

Fig. 3 *Experimental tuning of tunable MMI coupler against electrical current injection*

Conclusions: A tunable MMI coupler/splitter that can be electrically tuned all the way from a 90:10 to a 30:70 splitting ratio has been fabricated. Our zinc in-diffusion process allows for the selective definition of *p–i–n* regions and effectively regulates the current spreading. We believe that a more symmetric and wider tuning range is feasible with further device improvements. Nevertheless, to our knowledge, this amount of tuning in MMI couplers has never been experimentally demonstrated before. Furthermore, the process can be extended to a variety of highly functional photonic switches that operate on MMI effects.

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