Tunable multimode interference coupler

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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 contain-
ing 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 experi-
mentally 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 semi-
conductor 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
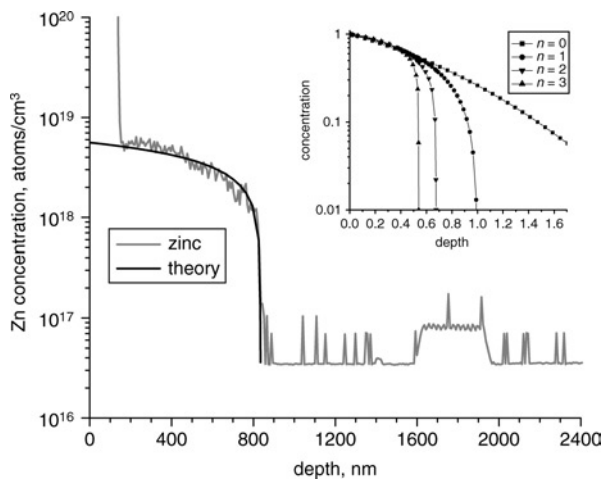of the technique for more sophisticated MMI-based devices.

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]:

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

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 coeffi-
cient. 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 depen-
dence 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
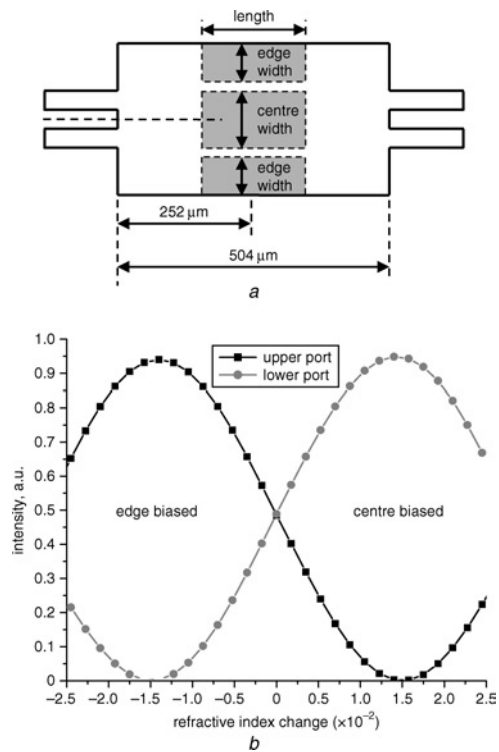keeping the remaining parameters constant.

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. 2a. 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. 2a,
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. 2b. 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.
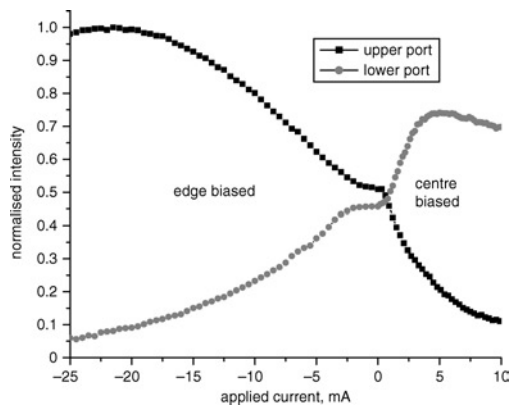
Conclusions: A tunable MMI coupler/splitter that can be electrically tuned all the way from a 90:10 to a 30:70 splitting ratio has been fabricated. Our zinc in-diffusion process allows for the selective definition of *p–i–n* regions and effectively regulates the current spreading. We believe that a more 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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Fig. 3 *Experimental tuning of tunable MMI coupler against electrical current injection*