

Polarization based modulation of splitting ratio in femtosecond laser direct written directional couplers

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ABSTRACT

This work characterizes a polarization dependent splitting ratio in femtosecond laser written waveguide directional couplers. In general, different coupling strengths exist for different polarization states of the input light. However, if the linear polarization state of the input light is not aligned with one of the symmetry axes of the system, an additional amplitude beating is imposed on the transfer of light in directional couplers of different interaction length. We present results for in-plane and out of plane directional couplers, which are supported by theoretical analysis. These new results provide insights for understanding and controlling polarization properties of directional couplers and larger photonic circuits.

1. Introduction

Polarization is a crucial property of light for encoding information for applications in photonic computing and communication [1]. For example, all-optical implementations are being explored in machine learning applications [2], and quantum light often uses polarization to create entangled states [3]. Since waveguide-based structures are important components for building integrated optical devices and circuits [4], many applications in topological photonics utilize waveguide arrays and evanescent coupling to demonstrate physical phenomena [5, 6]. On-chip quantum and data processing applications are also highly dependent on polarization properties [7–9]. Recent efforts have been directed towards polarization insensitive photonic devices [10]. While the impressive work demonstrates the ability to minimize polarization-dependent effects, in general polarization effects could be harnessed for further functionality. It is therefore necessary to understand how such optical devices respond to different polarizations in order to have full control on manipulating different states and preserving the quality of encoded information.

Previous work on femtosecond laser direct written (FLDW) photonic circuits has demonstrated different approaches to utilize polarization-dependent properties of integrated optical devices to let them act in lieu of bulk components, such as polarization beam splitters [11], waveplates [12] and retarders [13]. However, the characterization typically only considers vertical and horizontal linear polarization inputs, but not for arbitrary linear polarizations. Moreover, the devices were mostly coplanar, which gives an incomplete description of device behavior when considering three-dimensional structures. Szameit et al.

investigated how out of plane geometries affect coupling constants, but did not take input polarization into account [14]. Sansoni et al. fabricated out of plane directional couplers specifically so that the coupling was the same for horizontal and vertically polarized light [15]. Nevertheless, it was focused on finding a specific operating point for a fixed interaction region length. These works have shown that the x- and y-polarized light give rise to different periods of power exchange, but characterizations of other polarization states were unclear.

We present a general polarization-dependent effect where the orientation of linearly polarized incident light dictates the splitting ratio for each output port of a directional coupler and can modulate the maximum value attainable. To the best of our knowledge, this phenomenon has not been characterized in literature before. Moreover, we further demonstrate the effect in directional couplers extended to three-dimensional structures, where the two arms are not at the same depth from the substrate surface. The experimental results are in agreement with the theoretical description of the coupling for monochromatic light.

The FLDW method [16] focuses an ultrafast pulse laser to a highly confined volume, modifying the material through nonlinear absorption processes. The effect of the modification is dependent on both the fabrication parameters and the type of material [17]. In a variety of glasses (including the borosilicate glass used in this study), there is a positive refractive index difference between the modified region and the bulk, typically of the order $5\text{--}10 \times 10^{-3}$ [18,19]. When tracing the laser focus through the glass block, the resultant modified region therefore acts as a waveguide for light transmission. One of the strengths of FLDW inside a suitable material lies in its ability to create three-dimensional

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structures integrated in a single device. Recent work has been undertaken to utilize this capability to demonstrate topological and quantum phenomena [20–22]. However, to fully exploit this feature, it is crucial to understand how these out-of-plane geometries change the properties of the devices and the transmission for different polarization states.

Ultrafast laser-written directional couplers are investigated in this research as they are fundamental building blocks of optical circuits [23]. A waveguide directional coupler splits incident light into different output ports depending on the interaction length of the coupling region. It is formed by bringing two waveguides close to each other. Their function relies on evanescent coupling, which occurs when two waveguides are in close proximity and their evanescent fields overlap [24]. In this paper, the waveguide arm coupled to the input light will be referred to as the primary waveguide, and the other arm referred to as the secondary waveguide. The splitting ratio is the proportion of transmitted power in the primary and secondary waveguide outputs with respect to the input light of a directional coupler. The ratio varies with respect to the interaction region length of a directional coupler.

Fig. 1(a) shows the orientation of the input polarization angle θ with respect to the y-direction (vertical) of the directional couplers. Note that the red dashed line indicates the interaction region for evanescent coupling of the two arms of a directional coupler. Fig. 1(b) is a schematic diagram of the x-z plane view of a directional coupler with input light at one end of the primary waveguide and outputs at the other ends of the two arms. L_0 is the interaction region length for evanescent coupling and d is the separation distance between the two arms. Fig. 1(c) and (d) shows the waveguides being offset at an angle which we call ϕ , which is used when studying the effect on structures that are not coplanar.

We characterized experimentally the polarization effects on splitting ratio as a function of the interaction region length. This allows us to understand how the performance of directional coupler devices depends on polarization. Coupled mode theory was used to study the dependence of the splitting ratio on the polarization orientation angle and relative position of the waveguide arms, predicting an additional modulation effect which is in agreement with the experimental data. This gives insights into how we can control the fabrication and circuit design in order to improve the performance of devices by better understanding the polarization effects.

Below, Section 2 describes the background and theoretical study. Section 3 describes details of the experimental setup and the directional coupler fabrication process. Section 4 reports and discusses the experimental results and the results of extension to 3D structures. Section 5 gives the concluding remarks.

2. Background and theory

The splitting ratio r indicates the proportions of transmitted power in the primary and secondary waveguide outputs with respect to the input light of a directional coupler. According to coupled-mode theory [25, 26], the expression for r is given by

$$r = \frac{P_2}{P_1 + P_2} = \sigma^2 \sin^2\left(\frac{C}{\sigma} L_0\right) \quad (1)$$

where P_1 and P_2 are the output power of the primary and secondary waveguides respectively, C is the coupling coefficient between the two waveguides, σ is a dephasing term that depends on the waveguide asymmetry and L_0 is the length of the interaction region. The dephasing term σ is given by

$$\sigma = \frac{1}{\sqrt{1 + \left(\frac{\Delta\beta}{2C}\right)^2}} \quad (2)$$

where $\Delta\beta = |\beta_1 - \beta_2|$ is the difference of the propagation constants of the two waveguides [27]. Therefore, if there is some general asymmetry in the waveguide refractive index distribution, the maximum power

coupling ratio will be reduced to a fraction of the original. Nevertheless, the expression predicts a sinusoidal behavior with respect to the interaction region length. However, Eq. (1) does not fully consider polarization effects and asymmetry for different input polarization states.

When the input polarization is aligned with the principal axes of symmetry of the cross-section geometry (along x- and y-axis for $\phi = 0^\circ$ coplanar directional couplers as illustrated in Fig. 1(a)), the light propagates through the arms with a specific mode, which can be viewed as a superposition of symmetric and anti-symmetric modes [28]. Power exchange between the primary and secondary arms can then be explained in terms of the beating between the symmetric and anti-symmetric modes. However, when the input polarization is not aligned along either of these principal axes, both x-polarized and y-polarized modes are present, and the situation is more complicated. The x/y symmetric/anti-symmetric modes all have different propagation constants, therefore these four modes will all contribute differently to the total propagating wave.

Assume the two waveguides lie in the xz-plane, where z is the direction of light propagation through the waveguides (Fig. 1(a)). Birefringence caused by non-ideal device fabrication by FLDW, which often produces waveguides with non-circular cross-sections [29], leads to non-identical effective refractive indices of the primary and secondary waveguides for different input polarization states. Furthermore, the geometric configuration of the two waveguides leads to further asymmetry, particularly in the strain field, such that the propagation constants of the symmetric mode and the anti-symmetric mode of the x- and y-polarized light are therefore also different [30]. This difference leads to a change in the splitting ratio when the input polarization changes and is inherent to the geometry of the directional couplers.

Let the propagation constants of the x-symmetric (even) mode be denoted as k_{xe} and that of the x-anti-symmetric (odd) mode be denoted as k_{xo} . Similarly, the propagation constants for symmetric mode and anti-symmetric mode of the y-polarized modes are k_{ye} and k_{yo} respectively. We denote C/σ in Eq. (1) as κ , where the effective coupling coefficients κ_x and κ_y for the respective polarizations are related to the rate of power exchange between two waveguides (as described fully in the analysis below, see Eq. (8)).

Theoretically, the input light can be expressed as a sum of the symmetric and anti-symmetric modes with equal amplitude, and the beating between the modes creates a modulated envelope which manifests as the power exchange between the two arms of the directional coupler. The rate of power exchange is slightly different for polarized input light along the two principal axes, hence there will be an additional modulation to the splitting ratio for other polarizations. For linearly polarized light with the angle θ between the polarization axis and the vertical y-direction (Fig. 1(a)), the modulation is most pronounced at $\theta = \pi/4$. The derivation of this result is shown below.

2.1. Derivation for linearly x-polarized and y-polarized input light

Let $E_{xe}(z)$ represent the electric field amplitude for the propagating electric field corresponding to the x-symmetric mode as a function of z , omitting the time-varying component which is assumed to be the same for all terms. Similarly, for the other modes

$$\begin{aligned} E_{xe}(z) &= \cos(k_{xe}z), E_{xo}(z) = \cos(k_{xo}z), \\ E_{ye}(z) &= \cos(k_{ye}z), E_{yo}(z) = \cos(k_{yo}z) \end{aligned} \quad (3)$$

where z is along the propagation direction.

Consider input light polarized along the y-direction coupled to the primary waveguide arm. This input light can be expressed as a sum of the symmetric and anti-symmetric modes with equal amplitude. For unit amplitude input, at $z = 0$ we have $P_1 = 1$ and $P_2 = 0$. Assuming losses by absorption and scattering are negligible, we have $P_1 + P_2 = 1$ for all z since power is conserved. For simplicity, in the following, the power expressions P_x , P_y and P_θ refer to the output power of the x-polarized, y-

polarized and linearly polarized input light with polarization axis at an angle θ to the vertical y -axis. They represent power in the primary waveguide arm i.e. P_1 in Eq. (1). Note that P_2 in the secondary waveguide arm is therefore simply $1 - P_1$, being consistent with the notation in Eq. (1).

Let the wave amplitude in the primary waveguide corresponding to the y -polarized input light be E_y . Then

$$\begin{aligned} E_y(z) &= \frac{1}{2} (E_{ye}(z) + E_{yo}(z)) \\ &= \frac{1}{2} [\cos(k_{ye}z) + \cos(k_{yo}z)] \\ &= \cos\left(\frac{k_{ye} + k_{yo}}{2}z\right) \cos\left(\frac{k_{ye} - k_{yo}}{2}z\right) \end{aligned} \quad (4)$$

$$\begin{aligned} P_{\frac{\pi}{4}}(z = L_0) &= P_x \cos^2\left(\frac{\pi}{4}\right) + P_y \sin^2\left(\frac{\pi}{4}\right) \\ &= \frac{1}{2} (P_x + P_y) = \frac{1}{2} \left[\cos^2\left(\frac{\kappa_x}{2}L_0\right) + \cos^2\left(\frac{\kappa_y}{2}L_0\right) \right] \\ &= \frac{1}{2} \left[1 + \cos(\kappa_x L_0) + 1 + \cos(\kappa_y L_0) \right] \\ &= \frac{1}{2} \left[1 + \cos\left(\frac{\kappa_x + \kappa_y}{2}L_0\right) \cos\left(\frac{\kappa_x - \kappa_y}{2}L_0\right) \right] \end{aligned} \quad (10)$$

As k_{ye} and k_{yo} have similar but unequal values, the second cosine term is of much lower frequency than the first one. The expression therefore represents a modulated sinusoid with an envelope corresponding to the second term. The power flow in the waveguide is obtained by integrating the wave amplitude, therefore it is proportional to the square of the envelope. The power P_y corresponding to the y -polarized input with unit amplitude is given by:

$$P_y(z) = \cos^2\left(\frac{k_{ye} - k_{yo}}{2}z\right) \quad (5)$$

Similarly,

$$E_x(z) = \cos\left(\frac{k_{xe} + k_{xo}}{2}z\right) \cos\left(\frac{k_{xe} - k_{xo}}{2}z\right) \quad (6)$$

and

$$P_x(z) = \cos^2\left(\frac{k_{xe} - k_{xo}}{2}z\right) \quad (7)$$

The envelope shows how the power flow in the primary arm changes with distance. We define quantities κ_x and κ_y as follows:

$$\begin{aligned} \kappa_x &= k_{xe} - k_{xo} \\ \kappa_y &= k_{ye} - k_{yo} \end{aligned} \quad (8)$$

which is simply the inverse of the beat length between the two modes [31]. They can be interpreted as the effective coupling coefficients for the respective polarizations which manifests as the power exchange between the two arms of the directional coupler.

2.2. Derivation for arbitrary linearly polarized input light

Now consider an arbitrary linearly polarized light with polarization axis along θ coupled to the primary waveguide arm. Interference effects between modes (e.g. between k_{xe} and k_{ye}) are insignificant compared to the power exchange in directional couplers [31]. The overall power can therefore be found by decomposing the polarization vector into x - and y -components. Since the wave vector corresponding to this input is a vector sum of E_x and E_y components, for input light polarized along θ with unit amplitude we have:

$$\begin{aligned} P_{\theta}(z = L_0) &= P_x(z = L_0) \cos^2 \theta + P_y(z = L_0) \sin^2 \theta \\ &= \cos^2\left(\frac{\kappa_x}{2}L_0\right) \cos^2 \theta + \cos^2\left(\frac{\kappa_y}{2}L_0\right) \sin^2 \theta \end{aligned} \quad (9)$$

where the output power is measured at the output of a directional coupler with interaction distance L_0 .

Since the effective coupling coefficients of E_x and E_y are different, there will also be beating between the envelopes of the two waves. To demonstrate this behavior, we will give an example for $\theta = \pi/4$ where the beating is most pronounced when E_x and E_y have equal amplitudes:

The second cosine term shows an additional modulation to the sinusoidal variation of the splitting ratio with increasing interaction region length. This sinusoidal variation with wavenumber $(\kappa_x + \kappa_y)/2$ has a period between that of pure x - and y -polarized input, and the modulation envelope has a wavenumber proportional to $(\kappa_x - \kappa_y)/2$. This additional modulation is important to consider when using integrated photonic circuits comprising directional couplers with light of variable input polarization state. It should be noted that there is also a change of the polarization state for the output light from the mixing between different polarization states [32].

Finally, we point out that there exist interaction lengths for which the splitting ratio is independent of the input polarization. Polarization independence occurs when P_{θ} is independent of θ . From Eq. (9), we can observe that this occurs when $\kappa_x L_0 = \kappa_y L_0 + 2n\pi$. Rearranging terms, we have

$$L_0 = \frac{2n\pi}{|\kappa_x - \kappa_y|} \quad (11)$$

where n is any positive integer. This suggests that there is always some L_0 for which the splitting ratio is polarization independent. For practical considerations, L_0 should not be exceedingly large, therefore the difference between κ_x and κ_y cannot be too small.

3. Experimental setup

3.1. Fabrication system

The laser used in waveguide writing was a frequency-doubled regeneratively amplified Yb:KGW laser (Light Conversion Pharos SP-06-1000-pp) at 1 MHz repetition rate, 168 fs pulse duration, and 515 nm wavelength. A combination of a motorized rotating half-wave plate and a polarization beam splitter was used to adjust the average laser power.

A liquid-crystal on silicon spatial light modulator (SLM) (Hamamatsu Photonics X10468-09 (X)) is imaged by a 4-f system onto the pupil plane of the objective (0.5 NA; 20 ×; Zeiss Plan Neofluar), which then focused the laser into the specimen placed on the sample stage. The SLM was used to correct for system and sample aberrations [33]. System

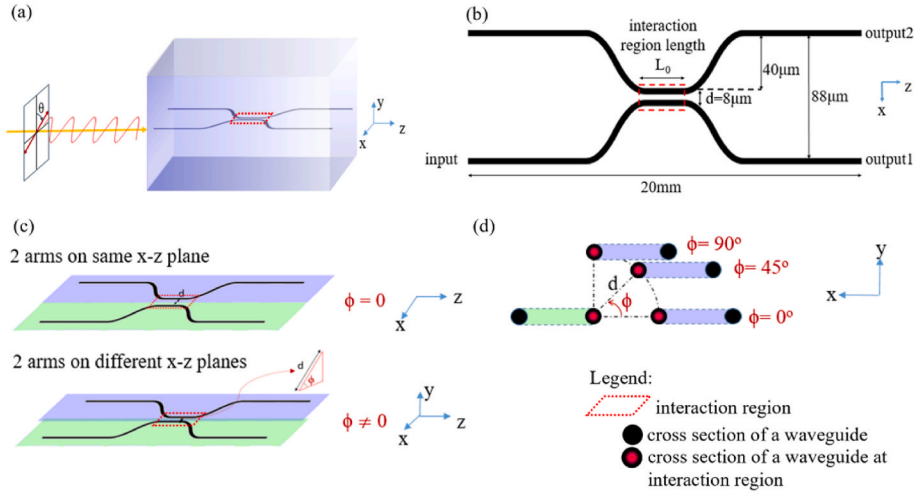


Fig. 1. (a) Schematic showing the input light polarization angle θ with respect to the vertical y-direction of the directional couplers. (b) 2D top view of a schematic directional coupler with two waveguides on same x-z plane. (c) 3D view of two waveguides lying on same or different x-z planes with a constant separation distance d slightly offset at an angle ϕ at the interaction region – the upper diagram shows when $\phi = 0$ and the lower when $\phi \neq 0$. (d) 2D cross-section view on x-y plane of two waveguides at different ϕ at the interaction region.

aberrations may arise from misalignment or imperfections of optical components, resulting in wavefront distortions, which are particularly relevant when focusing at high numerical aperture. The major sample aberration results from the refractive index mismatch between air and the sample, with the associated refraction leading to a focus distortion which varies when fabricating at different depths [34].

The devices were fabricated in borosilicate glass (Corning EAGLE 2000). The glass sample was fixed on a three-axis air bearing translation stage (AerotechABL10100L, xy-motion; ANT95-3-V, z-motion) for moving the sample relative to the laser focus.

Fig. 2(a) is a schematic describing the fabrication system. Achromatic doublet lenses L1 ($f = 60 \text{ mm}$) and L2 ($f = 150 \text{ mm}$) expand the laser beam onto the SLM, L3 ($f = 300 \text{ mm}$) and L4 ($f = 200 \text{ mm}$) formed a 4-f imaging system that relays the SLM pattern onto the objective pupil plane. LED illumination from the sample stage passed through the Dichroic Mirror (DC) and lens L5 ($f = 180 \text{ mm}$) was used to form an image on the CCD camera for monitoring the fabrication.

3.2. Fabrication parameters

Unless otherwise specified, the waveguides were written with a single scan at $150 \mu\text{m}$ depth from the surface, 8 mm/s scanning speed, and 110 nJ pulse energy measured at the objective pupil. These parameters were found by optimizing for the best transmission performance (minimizing propagation and coupling loss) as detailed in our

previous work [35,36].

After completion of the waveguide fabrication, the samples were polished by using a sequence of $30 \mu\text{m}$, $9 \mu\text{m}$, $3 \mu\text{m}$ and $1 \mu\text{m}$ polishing films. A layer of at least $150 \mu\text{m}$ glass was polished off both the input and output facets of the chip.

A directional coupler was created fabricating two waveguides separated by $88 \mu\text{m}$ at the input and output facets, then brought together in the middle of the sample with $8 \mu\text{m}$ separation in the interaction region (Fig. 1(b)). The S-Bends at either side of the interaction region yield a 0.04 mm shift in the x-direction over a 4 mm length. This corresponds to each section having a radius of curvature of 100 mm , which is chosen as sufficiently large to minimize bend losses.

Multiple sets of directional couplers were fabricated with different interaction region lengths from 2 mm to 10 mm in 0.5 mm steps to investigate variation of splitting ratio between two arms when polarization properties of input light were changed.

3.3. Characterization setup

To characterize and measure the performance of the fabricated devices, a testing rig was used to couple light from a fiber into the waveguides. The schematic is shown in Fig. 2(b). A fiber-coupled laser source (Thorlabs S1FC780PM) was coupled to a polarization-maintaining single mode fiber (Thorlabs PM630-HP (PANDA)) and the light emitted has a wavelength of 785 nm . All characterization in this work was

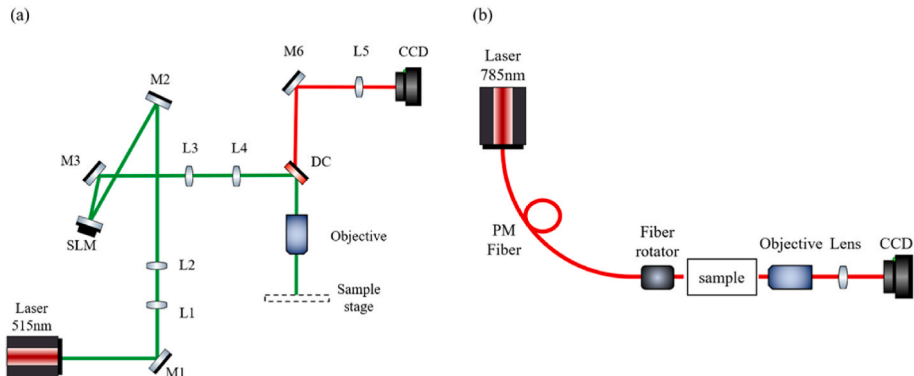


Fig. 2. Schematic of experimental setups used. (a) Fabrication setup: M: Mirror; L: Lens; SLM: Spatial Light Modulator; DC: Dichroic Mirror. (b) Characterization setup.

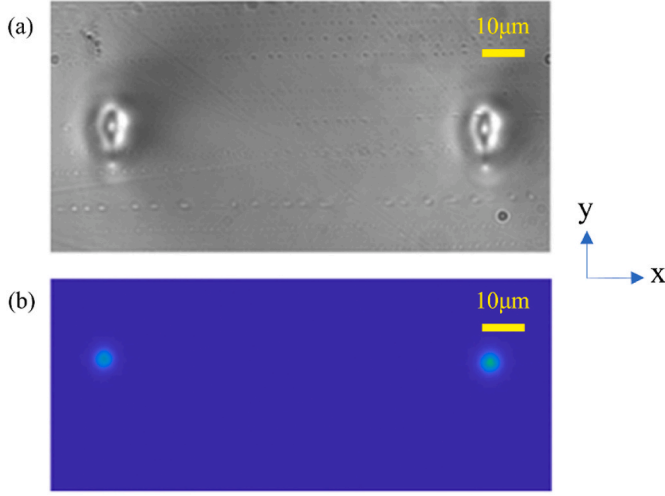


Fig. 3. View of experiment measurements at the output end of a directional coupler: (a) Output facet of primary and secondary waveguides under widefield microscope showing the cross-section of fabricated waveguides which are non-circular and elongated along the y-direction. (b) Microscopic image of laser light guiding modes at the two outputs.

performed with this monochromatic laser. The other end of the fiber was held by a fiber rotator (Thorlabs HFR007) which was mounted on a 6-axis stage (Thorlabs MAX600/M Series).

The glass sample was mounted onto a 3-axis translation stage (Newport M-562-XYZ-LH). The other end of the waveguides was imaged onto a CCD camera (Baumer TXD-14) using an objective (Olympus ULWD MS Plan 80 \times /0.75NA) and an achromatic lens (Thorlabs AC254-100-A-ML). The fiber was butt-coupled into the input of waveguide sample, with the fiber-tip in proximity (<1 μ m) to minimize coupling losses.

For directional coupler characterization, the fiber was coupled to one of the input waveguide arms. The splitting ratio of each directional coupler was then measured by integrating over each output using pixel values obtained from the images captured with the CCD camera. Fig. 3 (a) shows the output facet of the primary and secondary waveguides under LED illumination. Fig. 3(b) shows a sample image of the mode field for light output from the directional coupler device captured with the CCD camera. The mode field is circular and can be approximated by a Gaussian. The $1/e^2$ diameter is 6.12 μ m in the x-direction and 6.82 μ m in the y-direction.

4. Experimental results

We obtained measurements of the variation of splitting ratio against interaction region length when the input light had a linear input polarization at different angles θ to the vertical y-axis. We found that the coupling variation had a maximum period when the input polarization θ was at 0° and a minimum at 90° . The difference in period indicates a difference in the coupling coefficient C , which is in agreement with the theoretical analysis presented in Section 2. This observed polarization dependence is common to all directional coupler configurations provided there is a difference between κ_x and κ_y .

From the derivation in Section 2, we have shown that we only need κ_x and κ_y to know the variation for all other values of θ . The values for κ_x and κ_y are thus inferred from the experimental data measured at $\theta = 0^\circ$ and 90° by fitting the measured data to a sinusoid using Eq. (1) and minimizing least-square errors, with an additional phase that takes into account the coupling in the bend region that connects the input and output to the interaction region [37]. Let the period of the fitted variation be T , then κ_x and κ_y are given by

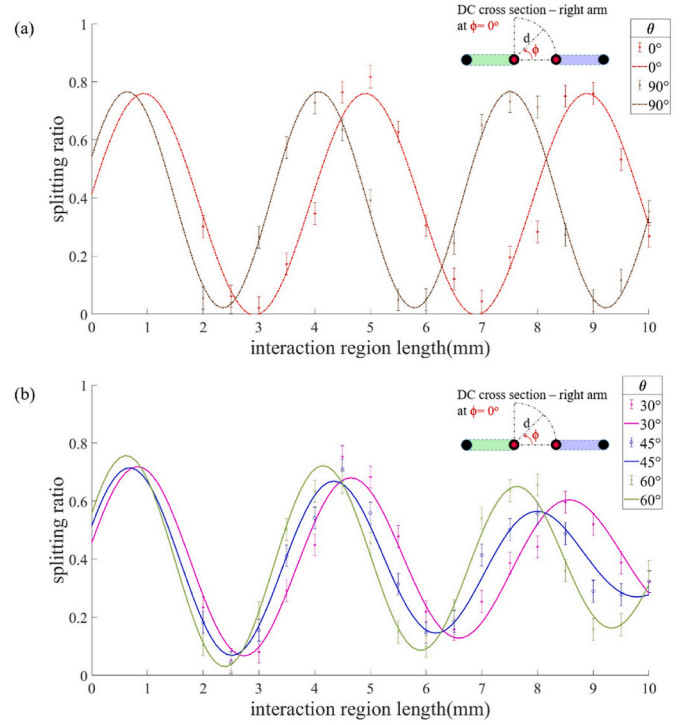


Fig. 4. Splitting ratio against interaction region length of laser-written directional couplers (DC) with input polarization angle θ (relative to the vertical symmetry axis), and ϕ at 0° . (a) Measured splitting ratios and least-squares fitted sinusoidal curves for θ at 0° and 90° . (b) Measured splitting ratios and theoretical predicted curves for θ at 30° , 45° and 60° . Error bars indicate measurement errors.

$$\kappa_x = \frac{2\pi}{T_x} \quad \& \quad \kappa_y = \frac{2\pi}{T_y} \quad (12)$$

We present in the following figures with the experimental data points and corresponding fitted curves. The main source of measurement error arises from the coupling between the fiber and the waveguide input. Measurements were performed on the set of directional couplers for at least five times, and the measured data points are shown with error bars which indicate the range of measured values.

Fig. 4(a) show the fitted sinusoidal curves for polarization angles $\theta = 0^\circ$ and 90° , which are used to infer the values of κ_x and κ_y using Eq. (12). The values are found to be $\kappa_x = 1.83$ rad/mm and $\kappa_y = 1.58$ rad/mm, which are typical of similar devices in literature [38,39]. Fig. 4(b) shows the predicted curves for polarization angles $\theta = 30^\circ$, 45° and 60° using Eq. (9). The results show that the curves predicted by theory are in good agreement with the measured data. They are no longer sinusoidal at a single frequency. Over several cycles a reduction in the maximum modulation is observed and the effect is most pronounced for a polarization angle of 45° , which is exactly the case of $\theta = \pi/4$ as shown previously in Eq. (10). The sum of least-squares error for sinusoidal curve fitting in Fig. 4(a) is 0.070, whereas the errors for the theoretical predictions in Fig. 4(b) are 0.038, 0.029 and 0.020 respectively for $\theta = 30^\circ$, 45° and 60° . This shows that the theory matches the measured result with high accuracy.

To further verify our understanding, we also fabricated waveguide arms of the DC that were slightly offset such that they have the same separation distance d but are on different xz -planes and at an angle ϕ from each other on the cross-section view (Fig. 1(c) and (d)). By compensating for the depth-dependent aberrations, we ensure that the cross-sections of the waveguides remain uniform at different depths. Comparing results for in-plane and out-of-plane directional couplers enables further understanding of the dependence on polarization.

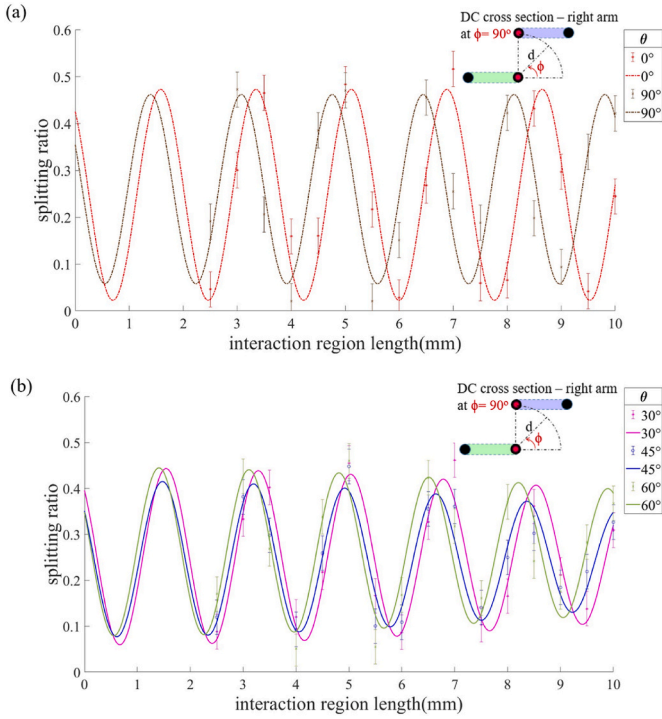


Fig. 5. Splitting ratio against interaction region length of laser-written DC with input polarization angle θ (relative to the vertical symmetry axis), and ϕ at 90° . (a) Measured splitting ratios and least-squares fitted sinusoidal curves for θ at 0° and 90° . (b) Measured splitting ratios and theoretical predicted curves for θ at 30° , 45° and 60° . Error bars indicate measurement errors.

Fig. 5 presents the data for directional couplers with waveguide arms at $\phi = 90^\circ$ with the same separation distance $d = 8 \mu\text{m}$. Similar to Fig. 4, the variation of splitting ratio with respect to interaction length is sinusoidal at a single frequency when the polarization angles match the symmetry of the system, whilst in Fig. 5(b) the maximum splitting ratio is modulated over several cycles, with the effect greatest for an input linear polarization at angle of $\theta = 45^\circ$. This confirms that the observed polarization phenomenon is generalizable to the out-of-plane geometrical configurations of directional couplers.

We also note that when $\phi = 90^\circ$, the splitting ratio has a limited upper bound of around 0.5. From Fig. 5(a), the values of κ are found to be $\kappa_x = 3.73 \text{ rad/mm}$ and $\kappa_y = 3.56 \text{ rad/mm}$, approximately doubled from the case of $\phi = 0^\circ$ in Fig. 4. This is partially due to the asymmetry of the waveguides causing dephasing between the coupling of the two waveguides. This effect is reflected by the σ term in Eq. (1). As a result, the amplitude of splitting ratio is reduced by a factor of σ^2 , and the period of the variation is also reduced by a factor of σ . The value of σ can be found by finding the ratio between the amplitudes for the respective splitting ratios of $\phi = 0^\circ$ and $\phi = 90^\circ$. This gives $\sigma_x = 0.635$ and $\sigma_y = 0.671$. From Fig. 3(a), we note that the modified refractive index region of the fabricated waveguide cross-section was elongated along the y-direction. Since the separation of the two waveguides from center to center is fixed at $8 \mu\text{m}$, the modified refractive index region of the upper waveguide overlaps partially with the lower one. This changes the refractive index profile in the interaction region between the two waveguides and affects the mode shape, hence the coupling between the two arms is also different. The measured values of κ resulted from a combination of both effects.

Fig. 6 shows the case for $\phi = 45^\circ$, where the geometry of the interaction region is effectively rotated by 45° . We observe that the splitting ratios for polarizations at $\theta = 45^\circ$ and 135° now show sinusoidal variation with a single frequency, matching the principal axes of the system. The values of κ are found to be $\kappa_{45^\circ} = 1.80 \text{ rad/mm}$ and $\kappa_{135^\circ} = 1.77 \text{ rad/mm}$.

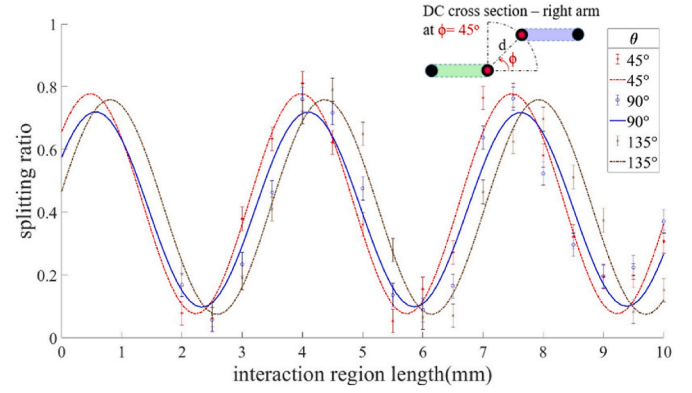


Fig. 6. Splitting ratio against interaction region length of laser-written DC with input polarization angle θ (relative to the vertical y-axis), and ϕ at 45° : dashed curves - least-squares fitted sinusoidal curves for θ at 45° and 135° ; solid curve - theoretical predicted curves for θ at 90° . Error bars indicate measurement errors.

mm. The amplitude of the splitting ratio for angles not along the principal axes displays a modulation similar to the case of $\phi = 0^\circ$ in Fig. 4.

Given the experimental results as shown above, we were able to correctly predict the variation for arbitrary linear input polarization given the geometry of the directional couplers. A simple prediction procedure can be performed as follows: Firstly we measure the κ_x and κ_y for any directional coupler geometry from finding the period of variation for polarization along the principal axes by minimizing least-square errors of data points for fitted sinusoidal curves. We can then use Eq. (9) to infer the variation for all other values of angle θ . This enables much quicker characterization and verification of directional coupler devices for more efficient prototyping and design processes.

Interestingly, we noticed that off-axis linearly polarized light gave the same power exchange for $+0$ and -0 states of polarization. We believe this is because the coupling is insensitive to the relative phase information and is solely determined by the magnitude of principal components. We therefore predict that for non-linearly polarized light, the variation can be predicted by the same procedure, i.e. projecting to the principal components and calculating the combined effect using Eq. (9). We also expect the phenomenon to showcase wavelength dependency. In particular, as wavelength increases, the asymmetry from the device geometry should be less significant, resulting in decreasing $\kappa_x - \kappa_y$, and the overall modulation will also become less apparent. Conversely, the modulation should be more pronounced at shorter wavelengths.

5. Conclusion

In summary, we have analyzed theoretically and observed in experiments that there is a modulation of the power splitting ratio of monochromatic light in a directional coupler when the input polarization does not align with the principal axes of the geometrical configuration. We also showed how different geometrical configurations of relative angular offset affect this variation. Supported by experimental results, we demonstrated that this modulation phenomenon is generalizable to out-of-plane geometrical configurations. We believe that this understanding is an important contribution to further optimizations of fabrication parameters in 3D photonic circuits. Combined with ways of controlling the birefringence of individual waveguides [40–42], this knowledge potentially enables new designs of applications with additional polarization related multiplexing or integrated polarization state readout, fully utilizing the three-dimensional capabilities of ultrafast direct laser writing.

CRediT authorship contribution statement

Zhi-Kai Pong: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Bangshan Sun:** Supervision, Conceptualization. **Zhenglin Li:** Validation, Investigation. **Patrick S. Salter:** Writing – review & editing, Supervision, Project administration. **Martin J. Booth:** Writing – review & editing, Supervision, Resources, Project administration.

Disclosures

The authors declare no conflicts of interest.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data underlying the results presented in this paper are not publicly available at this time but will be released through the Oxford University Research Archive.

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