Wide-Angle 1×3 Optical Power Divider in $LiNbO_3$ for Variable Power Splitting

Tzyy-Jiann Wang, *Member, IEEE*, Chih-Feng Huang, and Way-Seen Wang, *Member, IEEE*

***Abstract*—A new wide-angle 1×3 optical power divider with variable power splitting using substrate microprisms and two waveguide expanders is experimentally demonstrated by nickel diffusion in $LiNbO_3$. The produced substrate microprism with a graded-index profile and a depth-varied size is proved to be effective to produce phase-front tilt and field modification when in operation with two waveguide expanders. Experimental results show that the tuning range of the power splitting ratio can be $0.25 \sim 1.69$ and $0.18 \sim >1.09$ with low insertion loss for branching angle $\theta = 3^\circ$ and 4°, respectively. The fabricated devices have the features of low insertion loss, large branching angle, wide power tuning range, and easy fabrication.**

***Index Terms*—Integrated optics, lithium niobate, optical waveguide, power divider.**

I. Introduction

OPTICAL power dividers are essential and important components in optical integrated circuits. For various applications, input optical power is required to be distributed in several output waveguides with specified power-splitting ratio. According to the device structures, optical power dividers can be classified as three types: 1) branching waveguide; 2) directional coupler; and 3) multimode interference coupler. Among them, branching waveguides occupy the least device area and simultaneously have the flexibility of tunable power-splitting ratio and arbitrary power-splitting number. In order to construct any $1 \times \mathrm{N}$ optical power divider, 1×2 and 1×3 branching waveguides are required as elementary building blocks. For conventional 1×3 branching waveguide, the output power is mainly concentrated in the central output waveguide and only little power is transmitted through two sideward output ones [1]. Various structure designs are proposed in order to increase the output power in two sideward output waveguides. These designs for 1×3 branching waveguides include: 1) higher effective index in sideward output waveguides than that in the central output one [1]; 2) two low-index phase-front accelerators located in the in-between regions of two adjacent branching waveguides [2]; 3) a triangular region formed by putting the central branch at the branching side of a symmetric Y-branch [3]; 4) two high-index microprisms placed at the branching point of the conventional 1×3 branching waveguides [4]; and 5) a symmetric Y-branch waveguide with a phase-front retarder and a center branch located a coupling gap apart [5]. Most of the designs [(1), (2), and (4)] require extra regions with index higher than that of the waveguide or lower than that of the substrate. This increases the difficulty in the device fabrication. In the literature, only the idea proposed in (1) is realized by depositing a high-index cladding in the outer regions of the taper and the outer branches [6]. Previously, we proposed a new single-mode equal-power divider [7]. In the proposed device structure, no extra regions of indices different from those of waveguide and substrate are required. Simulation results for two-dimensional (2-D) step-index structure show that, by appropriate phase-front tilt and field modification, equal-power division and low insertion loss are attained for a large branching angle. In this work, the experiment consideration and demonstration of the proposed 1×3 optical power divider by nickel diffusion in $LiNbO_3$ are presented. The experiment results show that the proposed device structure with graded-index substrate microprism and waveguide expanders has the same good performance as that with step-index ones.

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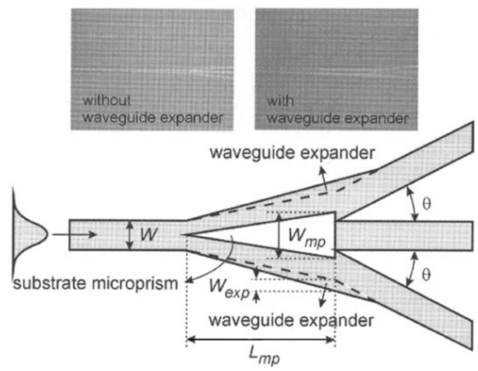

Fig. 1. Schematic diagram of the nickel film to produce the proposed 1×3 equal-power divider. (Inlet: the photographs of the nickel film to produce the proposed devices without and with waveguide expanders after liftoff in the photolithography process).

II. Design and Experiment

For the conventional 1×3 branching waveguide, the power quantity in two sides of the input optical field, which would be transmitted through sideward output waveguides, is far less than that in the central of the input optical field. After it enters into sideward output waveguides, because its phase-front is not vertical to sideward output waveguides, it will become radiation and disperses in the substrate. Hence, only little power is transmitted through two sideward output waveguides. In the proposed 1×3 power divider, substrate microprism and waveguide expanders, as shown in Fig. 1, are designed to facilitate the power transmission into two sideward output waveguides. The substrate microprism of width W_{mp} and of length

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L_{mp} can induce the required phase-front tilt and increase the power in two sides of the input optical field. The waveguide expanders of width $W_{\exp}$ can laterally stretch the input optical field and further increase the power in two sides of the input optical field. The previous simulation is for the 2-D step-index devices. Practical devices should be fabricated in three-dimensional (3-D) structures and depth effect of the proposed structure needs to be considered. Depth effect is mainly from the substrate microprism because its index is equal to the substrate index. When input optical field propagates through substrate microprism, some of the optical power leaks to the substrate due to the lack of optical confinement along the depth direction. Hence, insertion loss increases with microprism length. For 3-D step-index devices, only this effect is required to be considered. As to 3-D graded-index devices, not only this effect but also the effect of substrate microprism with a graded index distribution and a depth-varied size has to be considered.

In Fig. 1, the structure parameters, such as $W, L_{\mathrm{mp}}, W_{\mathrm{mp}}$, $W_{\exp}$, are referred to as the pattern parameters of nickel film. The graded-index waveguide fabrication process, such as metal diffusion or ion exchange, causes the structure variation of substrate microprism along the depth direction. The produced substrate microprism has a graded-index distribution and its range gradually expands with increase of depth. This graded-index substrate microprism with a depth-varied size inevitably affect the device performance. In practice, the microprism range (W_{mp} or L_{mp}) on the substrate surface is smaller than the size in the mask pattern for photolithography due to ion lateral diffusion. Though larger microprism width, W_{mp} is helpful to optical power splitting into two sideward output waveguides, W_{mp} in design should not be too large. Otherwise, the guiding ability of the device near substrate microprism becomes poorer and the propagation loss increases. In experiment, microprism width W_{mp} is set equal to waveguide wdith W (=6 μm). Besides, the 3-D index distribution in the vicinity of graded-index substrate microprism is not easy to be described and modeled accurately for simulation, especially on the place adjacent to substrate microprism and three output waveguides. Hence, experimental characterization for 3-D graded-index devices with proposed structures is necessary.

The proposed devices are fabricated on a z-cut, x-propagating $LiNbO_3$ substrate. First, a nickel film of thickness 300 Å with device pattern is formed on substrate by thermal evaporation and photolithography. Then the substrates are put in an oven at temperature of 850 °C for 45 min. Before measurement, both ends of the substrate are polished for end-fire coupling. Device characterization is made at the wavelength 632.8 nm for TM polarization. Normalized transmitted power is defined as the ratio of total output power from the device to that from straight waveguide. Power-splitting ratio γ is defined as the ratio of the power in the sideward output waveguide to that in the central output one. In the conventional 1×3 power splitter, most of the input power is transmitted in the central waveguide; thus, γ is always less than one.

III. Results and Discussion

First, the effect of a graded-index microprism on power splitting without waveguide expanders ($W_{\exp} = 0$ μm) is considered. Fig. 2 shows the dependence of the power-splitting ratio on the microprism length with $W = W_{\mathrm{mp}} = 6$ μm, for the branching angle $\theta = 1°, 2°, 3°, 4°, 5°$. It is found that the microprism indeed is effective in power splitting. For $\theta = 1°$, the power-splitting ratio is 1.1 when $L_{\mathrm{mp}} = 65$ μm. As L_{mp} increases from 60 μm to 110 μm, the power-splitting ratio is initially reduced and then increases again. When the L_{mp} increases under the fixed W_{mp}, the microprism shape becomes a triangle with a very acute angle. Due to finite resolution in photolithography, a pattern of shorter microprism with an additional taper region is formed on the substrate instead of the designed microprism pattern in the mask. Thus, the effect of lengthening the microprism in design is not so obvious. This situation also occurs in the initial section of three branch output waveguides. These taper regions result in the variation of the power-splitting ratio. For $\theta = 2°, 3°, 4°, 5°$, the power-splitting ratios for various L_{mp}s are below one. For smaller θ, the input power can be split into two sideward output waveguides not only by the microprism but also by the coupling through intermediate region between adjacent output waveguides. When θ is increased, this coupling becomes weaker and the power-splitting ratios are not larger than one anymore.

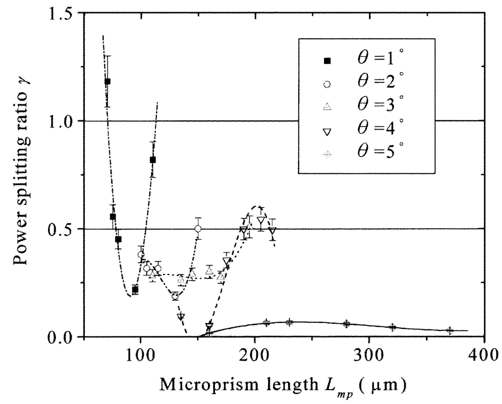

Fig. 2. Power-splitting ratio versus the microprism length without waveguide expanders ($W_{\exp} = 0$ μm) for the branching angle $\theta = 1°, 2°, 3°, 4°, 5°$ with $W = W_{\mathrm{mp}} = 6$ μm.

In order to increase the output power in sideward output waveguides for large θ, two waveguide expanders with $W_{\exp} = 2$ or 4 μm are appended to the devices. Fig. 3 shows the device characteristics of the power splitter with two waveguide expanders for $\theta = 3°$. The measurement results show that the power splitters with waveguide expanders of $W_{\exp} = 4$ μm can effectively increase the power in two sides of input optical field and, thus, the output power in two sideward output waveguides. As L_{mp} increases from 200 μm to 275 μm, the phase-front tilt of the input optical field can be adjusted and the power splitting ratio can be tuned from 0.25 to 1.69. It is noted that the normalized transmitted powers are all larger than 0.91, as shown in Fig. 3. The device characteristics of the power splitters with two waveguide expanders for $\theta = 4°$ are shown in Fig. 4. The maximum achievable power-splitting ratios are 0.55, 0.82, >1.09, for $W_{\exp} = 0, 2, 4$ μm, respectively. Their tuning ranges of γ are 0.45, 0.48, >0.91. The nonmonotonic variation of γ with increase of L_{mp} is due to power coupling, as mentioned previously. Besides that, the normalized transmitted power is slightly reduced with increase of L_{mp} in the range of 0.83 $\sim$ 0.53. It is found that for $\theta = 4°$, the appended waveguide expanders are more effective in tuning the power-splitting ratio with slighter reduction of the transmitted

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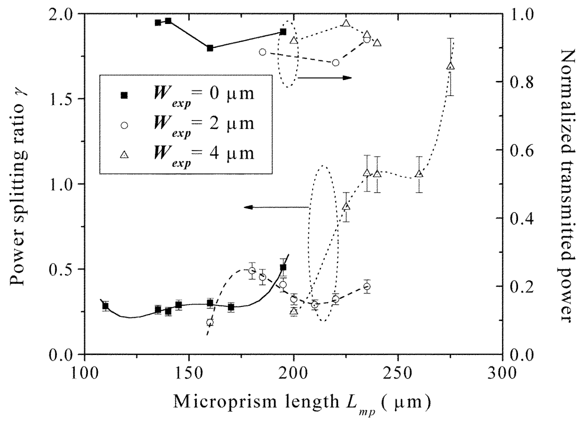

Fig. 3. Device characteristics of the power splitter with waveguide expanders of width $W_{\rm exp} = 0, 2, 4\ \mu$m for $\theta = 3^\circ$. (The error bar indicates the range of ±10% of the measured value).

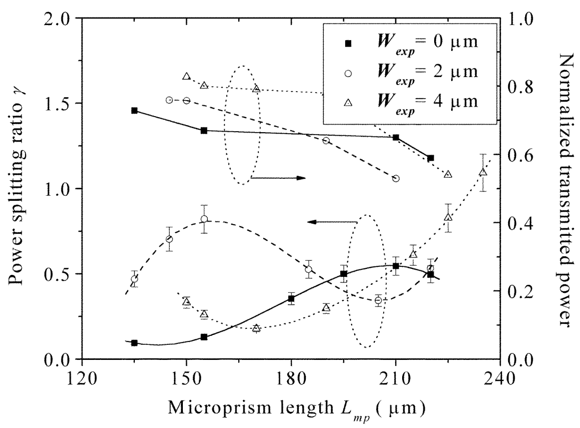

Fig. 4. Device characteristics of the power splitter with waveguide expanders of width $W_{\rm exp} = 0, 2, 4\ \mu$m for $\theta = 4^\circ$. (The error bar indicates the range of ±10% of the measured value).

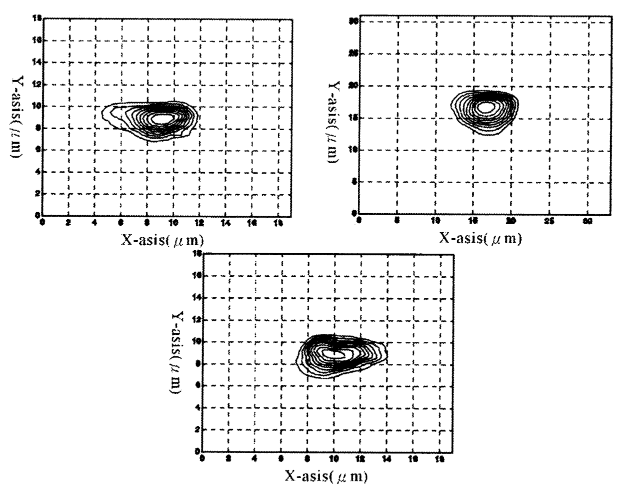

Fig. 5. Measured output optical field in three branching output waveguides with device parameters of $\theta = 3^\circ$, $L_{\rm mp} = 250\ \mu$m, and $W_{\rm exp} = 4\ \mu$m.

power than those for $\theta = 3^\circ$. With increase of $L_{\rm mp}$, the optical power in two sides of the optical field in the taper region is grown. When input optical field arrives the branching region, power coupling occurs between adjacent output branching waveguides through their gaps. For $\theta = 3^\circ$, the optical field incident on the branching region can be coupled back to the output waveguides through the more gradual waveguide splitting. Hence, less input power is lost and the corresponding transmitted powers are larger than 0.91. For $\theta = 4^\circ$, this power coupling is reduced due to larger branching angle and more power is lost by radiation through the adjacent regions of branching output waveguides. Hence, the transmitted power is slightly lower than that for $\theta = 3^\circ$. Even so, the transmitted power are still larger than 0.53 for $\theta = 4^\circ$ with an available power splitting ratio of 1.09. Fig. 5 shows the measured output optical field in three branching output waveguides with device parameters of $\theta = 3^\circ$, $L_{\rm mp} = 250\ \mu$m, and $W_{\rm exp} = 4\ \mu$m. It is found that the optical field is uniformly distributed in these branching output waveguides.

IV. Conclusion

We have successfully demonstrated a new wide-angle 1×3 optical power divider with variable power splitting using substrate microprisms and two waveguide expanders by nickel diffusion in $LiNbO_3$. Though the resultant substrate microprism have a graded-index profile and a depth-varied size, the experiment results show that, cooperating with two waveguide expanders, the fabricated devices can effectively produce required phase-front tilt and field modification to facilitate the increase of output optical power in two sideward output waveguides. For $\theta = 3^\circ$, the range of the power splitting ratio can be tuned from 0.25 to 1.69 with a normalized transmitted power of >0.91. For $\theta = 4^\circ$, the range of the power splitting ratio can be tuned from 0.18 to >1.09 with a normalized transmitted power of >0.54. The parameters of devices with demanded splitting ratio can be obtained from these experimental results by choosing appropriate $W_{\rm mp}, L_{\rm mp}$, and $W_{\rm exp}$. Besides, because the operation principle of the proposed device is not based on coupling or interference, it has much less wavelength dependence of power-splitting characteristics than the coupler-type or interference-type power splitter. To our knowledge, these are the best results reported so far. The device features of low insertion loss, large branching angle, wide power tuning range, and easy fabrication will make the fabricated devices suitable for various applications in power splitting.

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