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Multimode Interference Optical Power Splitter in Proton-Exchange LiNbO$_3$ Waveguides*

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Abstract: The self-imaging effect in graded-index waveguides using annealed proton-exchange (APE) technique in lithium niobate (LiNbO$_3$) waveguides is analyzed and simulated using the three-dimensional nonparaxial beam propagation method (BPM). On this basis, a 1×8 multimode interference (MMI) optical power splitter by APE technique in X-cut LiNibO$_3$ with Y-propagation substrate is fabricated. Measurements show that the device has realized eight powers splittings.

Key words: MMI; optical power splitter; nonparaxial BPM; APE LiNbO$_3$ waveguides

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1 Introduction

In the last few years, there has been a growing interest in the application of multimode interference (MMI) effect in integrated optics. Their unique properties, such as compact size, low loss, stable splitting ratio, low cross-talk, large optical bandwidth, insensitivity to polarization, and good fabrication tolerances have led to their rapid incorporation in more complex photonic integrated circuits[1~3]. Typically, these devices have been made using step index waveguide technology such as silica on silicon and GaAs/GaAlAs. This work uses graded-index lithium niobate (LiNbO$_3$) waveguides fabricated with annealed proton-exchange (APE) technique. The APE technique, using benzoic acid as the proton source, has become popular to form waveguides in LiNbO$_3$. Particularly the good power handling capability and the possibility to get high confinement has made this waveguide formation method the choice for integrated optics[4,5].

We first design a 1×8 MMI optical power splitter in graded-index LiNbO$_3$ waveguides using a three-dimensional nonparaxial beam propagation method (BPM)[6,7]. Then we describe an experimental realization of the device. Measurements show that the device has realized eight powers splittings.

2 Modeling and design

The LiNbO$_3$ waveguides exchanged from proton-rich melt such as benzoic acid exhibit step-like profiles. After annealing, some qualitative features are associated, in particular, a general increase in the waveguide depth with a corresponding decrease in the surface index and the evolving refractive-index profile changed. It will be graded-index distribution. Here we use a generalized Gaussian index model[8]:

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$$n(x) = n_b + \Delta n_s f(x), \Delta n_s = n_s - n_b,$$
$$f(x) = \exp\left[-\left(\frac{x}{d}\right)^{\alpha}\right] \quad (1)$$

where n_s and n_b represent the surface and bulk refractive index respectively, α represents a parameter associated with the shape of the profile (for example, the values $a = 1, 2, \gg 10$ refer to the exponential, Gaussian and step profiles respectively), and d is the effective waveguide depth defined by

$$n(d) = n_b + \Delta n_s / e \quad (2)$$

The device reported here is fabricated by APE technique in X-cut $LiNbO_3$ with Y-propagation substrate using benzoic acid as the proton source. At the operation wavelength of 1.55μm, the bulk refractive index n_b can be set 2.1456. Three parameters, Δn_s, d, and α in equation (1) are dependent on the exchange temperature and time (T_e, t_e), and anneal temperature and time (T_a, t_a). As for T_e= 210℃, t_e= 0.5h and T_a= 370℃, t_a= 3.5h, they can be set the empirical values as

$$\Delta n_s = 0.0846, d = 2.80\mu m, \alpha = 3 \quad (3)$$

Figure 1 shows schematic diagram of the 1×8 MMI optical power splitter. Considering of transversal diffusion of proton-exchange waveguide, mask width of all the waveguides are narrower than those values as shown in the figure.

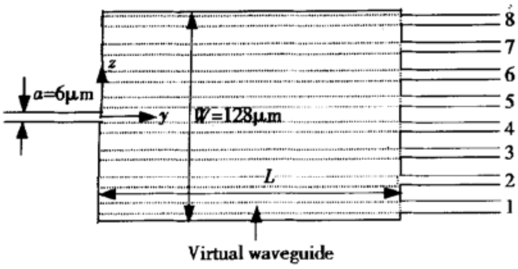

Fig. 1 Schematic diagram of 1×8 MMI splitter

Three-dimensional nonparaxial beam propagation method is a very useful tool to simulate light propagates in all kinds of medium. In MMI devices, when MMI width and other material parameters are fixed, the self-imaging effect mostly depends on the length L of MMI section. In order to monitor launch power from the input waveguide evolution in eight output waveguides, we put eight parallel virtual waveguides that run through all the MMI sections as shown in Fig. 1. Then we use the three-dimensional nonparaxial beam propagation method to simulate the power evolution in MMI section of the 1×8 MMI optical power splitter along the MMI section length, when a Gaussian input field propagates through the input waveguide and all eight virtual waveguides are uniform distributed. But the uniformity is not ideal. So we calculate the influence of center positions of the virtual waveguides. The calculated loss/uniformity is 0.07dB/0.0908dB at the MMI length of 2930μm with center position of the input waveguide is 0.0μm and those of the output ones are ±8.0, ±23.8, ±39.8, and ±55.6μm. Figure 2 shows the normalized power in eight virtual waveguides against MMI section length with optimized structure. From the results of simulation, we can draw the conclusion that the self-imaging effect can exist in graded-index waveguides, but the output waveguides are no more uniform distributed. They are deviated some value.

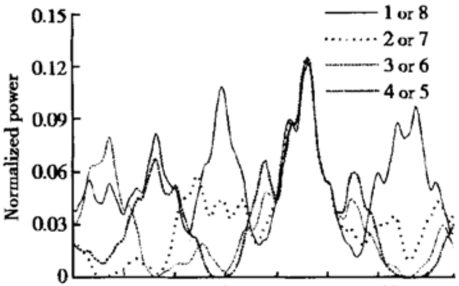

Fig. 2 Normalized power in eight virtual waveguides against MMI section length with optimized structure

In order to make the device fiber compatible, eight low-loss single-mode waveguides with S-shaped curve are placed at the output waveguides[9]. The S-bends are also designed using nonparaxial BPM. Allowing a maximum bend loss of 0.1dB, which is a requirement for APE $LiNbO_3$

waveguides to have negligible bend loss, the length of the output S-bends is 7000μm. Figure 3 shows a Gaussian input field propagates through the S-bend associated with output 1 or 8. As seen, most input power has kept in the S-bend.

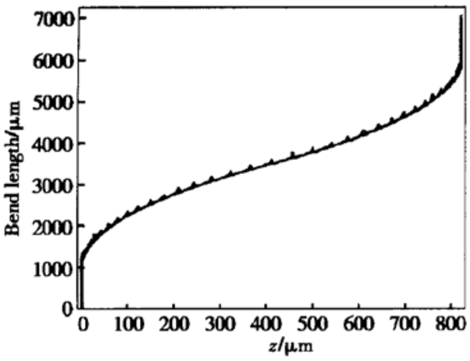

Fig. 3 Simulation of S-bend associated with output 1 or 8 using nonparaxial BPM

3 Experimental results

The MMI optical power splitter is fabricated in X-cut Y-propagation LiNbO$_3$ substrate. The channel waveguides are prepared, first by carrying out photolithography to create masked regions of aluminum (Al) on the substrate (Considering of side diffusion, the channel waveguides are narrower mask opening than the last required width). Then the LiNbO$_3$ sample is immersed in a benzoic acid melt at around 210℃ (lower than its boiling point 249℃) for exchange time of 30min. During the exchange reactions, Li$^+$ ions diffuse from the crystal surface, and H$^+$ ions diffuse into the crystal to replace Li$^+$. Figure 4 shows parts of 1×8 MMI LiNbO$_3$ splitter after proton-exchange in benzoic acid. After the proton exchange and removal of the exchange mask, the sample is annealed at 370℃ in an oxygen atmosphere for 3.5h. This step proves to be necessary to lower waveguide propagation loss.

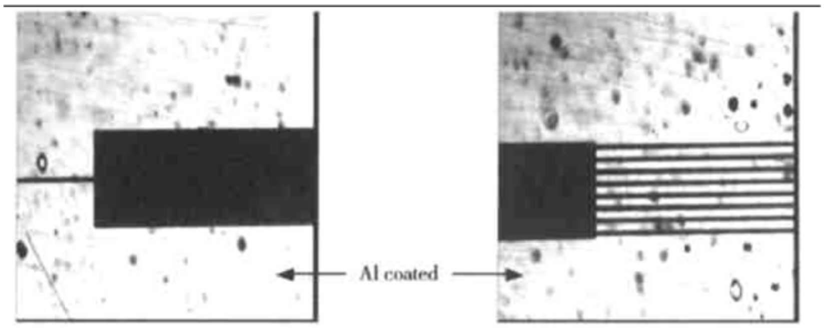

Fig. 4 Parts of 1×8 MMI LiNbO$_3$ splitter after proton-exchange in benzoic acid

The fabricated device is measured at $\lambda = 1.55\mu$m by using a pigtailed DFB-LD. A lensed fiber is used to couple the light into the input waveguide via butt coupling. Light output from the output waveguides is collected by a laser-diode lens and is examined by a combination of an infrared video camera and a TV monitor. Figure 5 shows the near field beam patterns of the output images at the beginning of S-bends. Figure 6 shows the two images of the splitter at the end of S-bends with pitch of 250μm. As seen, the device has realized eight powers splittings. Results show that the output images are not so ideal as simulated results.

Fig. 5 Output images of 1×8 MMI LiNbO$_3$ splitter at the beginning of S-bends

This can be originated from index profile approximation and fabrication error, which will be improved in the further work.

Fig. 6 Two images of 1×8 MMI $LiNbO_3$ splitter at the end of S-bends Pitch is $250\mu m$.

4 Conclusion

We have achieved in fabricating the 1×8 MMI optical power splitter in graded-index APE $LiNbO_3$ waveguides. Measurements show that the device has realized eight powers splittings. This work shows that MMI devices can be realized in graded-index waveguides. There are potential prospects of using APE technique in $LiNbO_3$ material together with MMI splitters for high performance and cost effective solution.

References

[1] Bryngdal O. Image formation by self-imaging techniques. J Opt Soc Am, 1973, 63(4): 414

[2] Bachmann M, Besse P A, Melchior H. General self-imaging properties in $N\times N$ multimode interference couplers including phase relations. Appl Opt, 1994, 33(16): 3905

[3] Soldano L B, Pennings E C M. Optical multi-mode interference devices based on self-imaging: principles and applications. J Lightwave Technol, 1995, 13(4): 615

[4] Howerton M M, Burns W K, Skeath P R, et al. Dependence of refractive index on hydrogen concentration in proton exchanged $LiNbO_3$. IEEE J Quantum Electron, 1991, 27(3): 593

[5] Wong K K. Integrated optical waveguide devices fabricated by proton-exchange: a review. SPIE, 1988, 993: 13

[6] Weiping H, Xu Chenglin, Chu Sai-Tak, et al. The finite-difference vector beam propagation method: analysis and assessment. J Lightwave Technol, 1992, 10(3): 295

[7] Chung Y, Dagli N. A wide-angle propagation technique using an explicit finite difference scheme. IEEE Photonics Technol Lett, 1994, 6(4): 540

[8] Nikolopulos J, Yip G L. Theoretical modeling and characterization of annealed proton-exchanged planar waveguides in z-cut $LiNbO_3$. J Lightwave Technol, 1991, 9(7): 864

[9] Ma Huilian, Yang Jiangyi, Jiang Xiaoqing, et al. Compact and economical MMI optical power splitter for optical communication. Chinese Journal of Semiconductors, 2000, 21(10): 966

质子交换铌酸锂波导 MMI 光功分器*

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摘要: 利用三维非旁轴近似光束传输法对退火质子交换铌酸锂渐变折射率分布波导中的自镜像效应进行分析与模拟. 在此基础上, 利用退火质子交换技术在X切Y传铌酸锂衬底上进一步制作了 1×8 MMI光功分器. 测试表明器件实现了1路分成8路的光功分功能.

关键词: 多模干涉; 光功分器; 非旁轴近似光束传输法; 退火质子交换铌酸锂波导

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