Comparison of Measured Losses of Ti:$LiNbO_3$ Channel Waveguide Bends

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Abstract—**We report measured losses of Ti:$LiNbO_3$ waveguide S-shaped bends designed by using sine, cosine-generated curves, two arcs, and two arcs with a connecting straight guide. Experimental results confirm that the cosine-generated curve provides the best performance.**

I. Introduction

WAVEGUIDE BEND is a basic building block for waveguide devices. It is used to shift the lateral position of waveguides. The lateral offset h can be negotiated over certain length l by simply using abrupt angle bends, i.e., a straight waveguide at an angle to connect the two parallel waveguides [1], [2]. Since dielectric waveguides are weakly guided, radiation loss occurs whenever the direction of the guided optical beam is changed. To reduce such a loss, S-shaped curves, e.g., two arcs with constant curvature, sine-generated curve, and coherent coupling bends have been used [1], [3]–[7]. They indeed outperform simple, abrupt angle bends. It is a common practice nowadays to design S-shaped bends using the sine-generated curve. Although the sine-generated curve is a standard practice, theoretical results indicate that S-shaped bends based on the cosine-generated curve can provide a better performance for most of the design parameters encountered [8], [9]. As discussed in [9], both the straight-curved transition and the curvature of the S-bend contribute to the overall loss. Although sine-generated curve has a smoother straight-curved transition, it has a larger maximum curvature, hence, a higher overall loss than that of the cosine-generated curve.

Since S-shaped bends have been proven to be better than simple angle bends, they have also been used in other applications than fiber pigtailing. The Mach–Zehnder interferometric modulators, for example, have one input guide and two arms with a separation in the range of tends of microns. The splitting of the input power is achieved by using a Y-junction. The two output waveguides of the Y-junction must be bent to form two parallel arms of the interferometric modulator. S-shaped bends have been used to negotiate such bends. Two S-shaped bends have also been used to form the Y-junction. Since the typical lateral offset is quite small in such applications, the length of the bend is also shorter than that used for fiber pigtailing. It is well known that the curvture increases as the lateral offset and length are reduced proportionally [5]. To keep loss low, it is more appropriate to scale h to l^2 [5]. Since it is always desirable to maintain lengths of integrated optical devices short, it is still interesting to compare different designs to see how the losses increase as h and l are reduced proportionally.

In this letter, we present experimental data to confirm that S-shaped bends designed by using the cosine-generated curve provide the best performance.

II. Experimental Procedures

We designed a series of mask patterns using the OPTOMASK package. We used two arcs (R), two arcs with a straight connecting waveguide (L), cosine-generated curve (C), and sine-generated (S) curve to form S-shaped bends. The lateral offset chosen is 364 μm and the length is 12 mm. The nominal angle of these S-shaped bends, defined as $\tan^{-1}(h/l)$, is 1.7374°. For the two arcs, the radius used is 99 mm. For the two arcs with a connecting straight waveguide, the radius for the arcs is 20 mm. The connecting waveguide is 10.72-mm long. The mask patterns are shown in Fig. 1 with an x-to-y aspect ratio of 1:20. In addition to S-shaped bends, we also put four straight waveguides on the mask for calibration. The width of Ti stripes used in forming waveguides is 3.6 μm.

The lateral position of the center y of the waveguide along the length x is described by the following equations for the sine- and the cosine-generated bends, respectively,

$$y = \frac{h}{l}x - \frac{h}{2\pi}\sin\left(\frac{2\pi}{l}x\right), \tag{1}$$

$$y = \frac{h}{2}\left(1 - \cos\left(\frac{\pi}{l}x\right)\right). \tag{2}$$

The curvature (R) of the two-arc design is given by

$$R = \pm\frac{l^2}{4h}\left(1 + \frac{h^2}{l^2}\right). \tag{3}$$

To compare losses of S-shaped bends with the same nominal angle but different lengths, we also designed a series of R-C-S bends with a nominal ange of 0.5°. The lengths used are 1, 2, 3, and 4 mm.

Waveguides were fabricated by using the standard Ti-indiffusion technique on x-cut, y-propagating $LiNbO_3$. After

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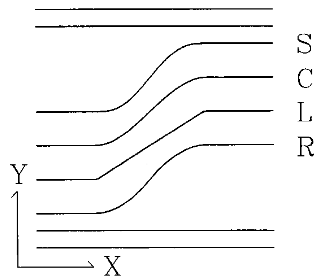

Fig. 1. Mask patterns of S-shaped bend designs. They are shown with an aspect ratio of 1:20. Four designs, including, two arcs (R), two arcs with a connecting straight guide (L), cosine-generated curve (C), and sine-generated curve (S) are used. The lateral offset is 364 μm. The length is 12 mm. Straight waveguides are included for calibration.

diffusion, the substrates were cut and polished. A diode laser at 0.83 μm was used to characterize these waveguide structures. The transmission coefficients were measured by using a power meter. The average transmission coefficient for straight waveguides was normalized to unity. For comparison among R-L-C-S bends, three wafers were measured. For comparison of losses of S-shaped bends with different lengths, one wafer was characterized. For each length, however, three different S-shaped bends were tested.

III. Results and Comparisons

Measured results of different S-shaped bends with $h = 364$ μm and $l = 12$ mm are summarized in Table I. Our experimental results confirm that the S-shaped bend designed by using the cosine-generated curve has the lowest loss.

Results of bends with different lengths but the same nominal angle are shown in Fig. 2. Only TM polarization is presented. Similar results were also observed using the TE polarization. Because of increase in curvature, losses increase sharply when l is reduced to less than 2 mm while h is reduced proportionally to less than 17.5 μm. Among tested bends, the cosine-generated curve still has the best performance. If l is required to be short, simple angle bend shall be considered. For angle bends, h and l can be reduced proportionally without increasing the loss.

IV. Summary

In summary, we have measured and compared losses of various Ti:$LiNbO_3$ S-shaped waveguide bends, including sine, cosine-generated curves, two arcs and two arcs with a straight connecting guide. The cosine-generated curve provides the best performance.

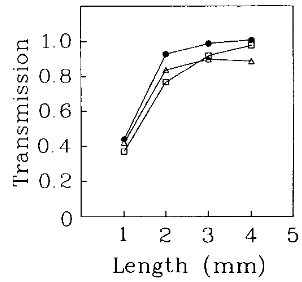

Fig. 2. Transmission coefficients of nominally 0.5° S-shaped bends, including cosine-generated curve (dot), two-arc design (triangle), and sine-generated curve (square) versus the length of bends.

TABLE I
Comparison of Losses of S-Shaped Bend Designs

	Transmission Coefficient (%)			
	R	C	S	L
TE	74.3	86.5	74.3	34.0
TM	84.5	95.5	94.5	46.5

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