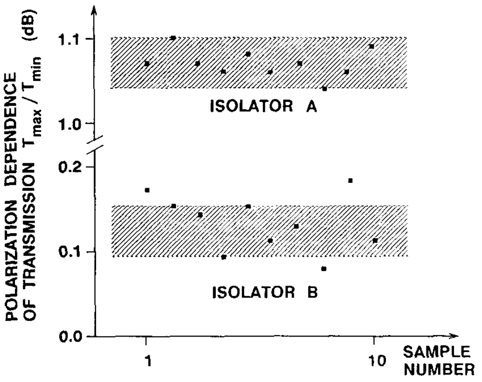

Fig. 3. Measurements of the polarization dependence of transmission of two pigtailed optical isolators. The shaded areas indicate the manually measured values including ±0.03 dB uncertainty. Ten singular value measurements of each isolator are plotted, each measured with different input and output birefringences (different settings of PT1 and PT2 in Fig. 2).

ranged from 0.08 to 0.18 dB, yielding a mean ± standard deviation of 0.131 ± 0.033 dB. Excellent agreement between the two methods is apparent, confirming the accuracy of this fast, deterministic technique. Measurement of a Jones matrix and calculation of its singular values took less than 2 s.

## SUMMARY

A new technique has been demonstrated for measuring the variation in transmission of linear, time-invariant optical devices, over all SOP's, by measuring the polarization responses to three stimulus SOP's. For the first time, this technique provides a deterministic, analytically complete means to characterize the polarization sensitivity of devices such as isolators or directional couplers. By eliminating the search over polarization space it allows a completely specified test suitable for comparisons and standards. The measurements were performed in less than 2 s, and resulted in the same values of polarization dependence obtained by tedious manual measurement.

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# Measurement of Mode Splitting in Asymmetric *Y*-Junctions

J. J. G. M. van der Tol and J. H. Laarhuis

***Abstract*—A measurement procedure is presented for the determination of mode splitting (or mode sorting) in asymmetric *Y*-junctions. This procedure avoids measurement errors introduced by bends, tapers, small damages in the waveguides outside the coupling region, variation in fiber-chip coupling etc. It is based on the analysis of the normalized coupled power in an optical coupler in which a mode splitter is used. The method is illustrated with a mode splitter on lithium niobate. A value of 29.2 ± 0.5 dB for the suppression of the unwanted mode is found, showing the applicability of the procedure.**

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## I. INTRODUCTION

RECENTLY, there has been an interest in asymmetric *Y*-junctions in integrated optics. These devices have been used as mode splitters in digital optical switches [1], 3 dB-couplers [2], and polarization splitters [3]. Such *Y*-junctions are designed to give low conversion of the local modes in the waveguide structure. Advantages of these mode splitters are reliability, tolerance in fabrication and wavelength (and possible polarization) insensitivity.

The performance of the above mentioned components depends on the distribution of the transmitted power over the outgoing modes, i.e., on the mode splitting, of the asymmetric *Y*-junctions. An experimental determination of this distribution is important for characterizing the components and for

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evaluating the design of the mode splitters. In this letter an experimental procedure is presented for unambiguous characterization of mode splitters.

At first glance characterization of mode splitters seems quite simple. If one injects a fundamental mode in a bimodal waveguide which is connected to the assymetric *Y*-junction, the intensity distribution at the outputs would show the mode splitting. In practice, however, the situation is more complicated. Small damages in the output waveguides, the effect of *S*-bends and tapers, and differences in efficiency of outcoupling influence the output intensities of the *Y*-junction. This results in an error in determination of the mode splitting. Such an error could be corrected by also injecting the higher-order mode in the bimodal input waveguide, if the coupling between the modes is assumed to be reciprocal. Unfortunately, techniques for selectively exciting a first-order mode (e.g., grating or prism-coupling) are rather cumbersome. Finally, it is noted that the problem can not be circumvented by injecting light in the branches of the *Y*-junction. This would require determination of the distribution of power over the two modes of the bimodal waveguide. These modes, however, cannot be separated without a reliable mode splitter.

In view of these problems an alternative procedure is designed, which relies on the interference of two modes in a bimodal waveguide located between the asymmetric and a symmetric *Y*-junction (see Fig. 1). This procedure is based on the modal description of optical couplers, given in Section II. The procedure itself is described in Section III and illustrated in Section IV with an experimental coupler on lithium niobate.

## II. THEORY

The optical coupler (Fig. 1) consists of three different sections. The input section is a symmetric, the output section an asymmetric *Y*-junction. Between these two *Y*-junctions a longitudinally invariant bimodal section of length $L$ is placed. These three sections are characterized by the relation between the complex amplitudes of the modes describing the incoming optical field and those describing the outgoing field:

$$\vec{a}_{\text{out}} = \vec{\vec{S}}\vec{a}_{\text{in}} \tag{1}$$

where the vectors represent the optical field in terms of the complex amplitudes of the two modes. The subscripts of the vector components $a_1$ and $a_2$ refer to the amplitudes of the modes in channel 1 and 2, respectively, at the input and output of the coupler. At the interfaces between the different sections, however, they refer to the fundamental and the higher-order mode of the bimodal section. The attenuation of both normal modes is assumed to be equal. Thus, the device can be analyzed as if it were lossless since attenuation can be factored out. This implies that the coupling between the modes is reciprocal. Using this property the coupling matrices of the specific sections of an optical coupler can be constructed:

$$\vec{\vec{S}}_{\text{out}} = \begin{pmatrix} ce^{i\Phi_{11}} de^{i\Phi_{12}} \\ de^{i\Phi_{21}} ce^{i\Phi_{22}} \end{pmatrix}, \quad \vec{\vec{S}}_{\text{bimodal}} = \begin{pmatrix} e^{-i\beta_1 L} & 0 \\ 0 & e^{-i\beta_2 L} \end{pmatrix},$$

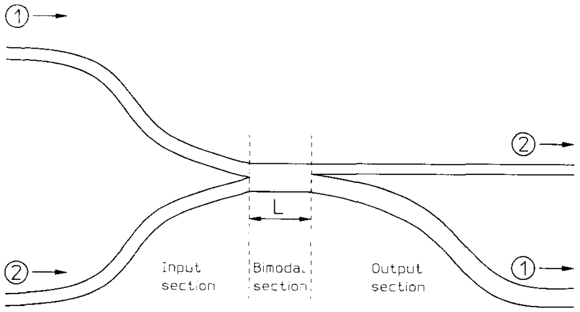

Fig. 1. General layout of the coupler. $L$ is the length of the interference region.

$$\vec{\vec{S}}_{\text{in}} = \begin{pmatrix} ge^{i\Psi_{11}} he^{i\Psi_{12}} \\ he^{i\Psi_{21}} ge^{i\Psi_{22}} \end{pmatrix} \tag{2}$$

with

$$c^2 + d^2 = g^2 + h^2 = 1$$

where $L$ is the length and $\beta_{1,2}$ the propagation constant of the fundamental mode, respectively the higher-order mode, of the bimodal region. The complex coupling coefficients are described by their moduli $c$, $d$, $g$, $h$ and by the phases $\Phi$ and $\Psi$. For ideal operation as a mode splitter the off-diagonal elements of the coupling matrices of a *Y*-junction should be zero. In that case each channel mode of the branches couples completely with one of the modes in the bimodal region, and vice versa. This requires [4] that there is a large asymmetry in the structure, i.e., a large difference in the propagation constants of the channel modes, and that the structure converges or diverges slowly. The operation is deteriorated by mode conversion, which is the cumulative buildup of the higher-order normal mode at the expense of the fundamental normal mode (and vice versa), resulting in nonzero off-diagonal elements in the coupling matrix of the asymmetric *Y*-junction. The behavior of the optical coupler can be described by multiplication of the matrices in (2):

$$\vec{\vec{m}} = \vec{\vec{S}}_{\text{out}} \vec{\vec{S}}_{\text{interference}} \vec{\vec{S}}_{\text{in}}. \tag{3}$$

The lossless optical coupler is characterized by the normalized coupled power $G_N$. This is the power emerging from waveguide 1 (respectively 2) when launching unity power into waveguide 1 (respectively 2). It is found by multiplication of $m_{21}$ with its complex conjugate. From (2) and (3) straightforward matrix calculus leads to an expression for $G_N$:

$$G_N = d^2g^2 + c^2h^2 + 2dgch\cos\left[(\beta_1 - \beta_2)L + \Omega\right] \tag{4}$$

with

$$\Omega = \Phi_{11} - \Phi_{21} + \Psi_{21} - \Psi_{22}.$$

## III. MEASUREMENT PROCEDURE

The power $P_{ij}$ from output port $j$ when injecting power $P_0$ in input port $i$ is given by

$$\begin{aligned} P_{ij} &= \alpha_{i,\text{in}}\alpha_{j,\text{out}}(1 - G_N)P_0 \qquad (i \neq j) \\ P_{ij} &= \alpha_{i,\text{in}}\alpha_{j,\text{out}}G_N P_0 \qquad (i = j) \end{aligned} \tag{5}$$

The attenuation factors $\alpha$ describe the possible losses in the input and output channels of the coupler. From (5) the ratio the attenuation factors for the input channels can be found:

$$\alpha_{1,\mathrm{in}}/\alpha_{2,\mathrm{in}} = (P_{12}P_{11}/P_{21}P_{22})^{1/2}. \tag{6}$$

For the output channels a similar relation holds. Furthermore, a quotient can be constructed which is independent of the attenuation factors:

$$P_{12}P_{21}/P_{11}P_{22} = (1 - G_N)^2/G_N^2. \tag{7}$$

From this equation the normalized coupled power $G_N$ can be derived:

$$G_N = \left(1 + (P_{12}P_{21}/P_{11}P_{22})^{1/2}\right)^{-1}. \tag{8}$$

By eliminating the attenuation factors in this way the value of $G_N$ is corrected for the variation in the butt-coupling for small damages in the waveguides outside the coupling and interference regions, for loss differences in the input and output channels, and for variation in the detection efficiency.

The value of $G_N$ is determined for identical structures with varying interference length. Using a least squares procedure these experimental numbers can be fitted to (4). From the mean value and the amplitude of the oscillating function $d^2$ and $g^2$ (or $c^2$ and $h^2$) can be derived. Three assumptions are made in using this procedure:

1) To accurately determine the interference between the two modes in the bimodal region the differences in their loss must be negligible over a few coupling lengths. In general, this condition poses no problems as is testified by the numerous directional couplers presented in the literature.
2) The coupling of the modes within the asymmetric $Y$-junction is assumed to be reciprocal. This means that differences in losses between the different modes can be neglected in the (relatively short) region where the two branches are close enough for coupling between channel modes. This requires well-guided modes in this region. However, outside the coupling region loss differences may occur.
3) There must be a clear difference in the behavior of the two $Y$-junctions in order to separate their parameters, since the elements of their respective coupling matrices appear symmetric in (4).

This measurement procedure is well suited for the characterization of mode splitters. If the amplitude of the cosine in (4) is 0.03, which is easily detectable, the mode suppression, which is defined as the $-10^{*10}\log(d^2)$, is more than 30 dB. On the other hand the procedure appears to be less suited if the asymmetric $Y$-junction is close to being a 50/50 power splitter; in that case a change of 0.01 in the amplitude results in a large change ($>$ 10%) in the value of the matrix-elements. The symmetric $Y$-junction does not have to be a perfect 50/50 power splitter. If it is, however, it simplifies the fitting procedure, since the observed oscillation is then always around 0.5. Furthermore, also other important parameters are determined with this procedure (ratio of attenuation factors, coupling length, splitting ratio of symmetric $Y$-junction), which allows for testing the design and the fabrication of the various parts of the coupler.

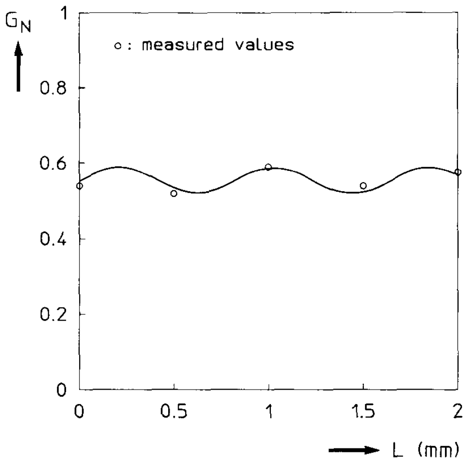

Fig. 2. Normalized coupled power $G_N$ as a function of $L$ for the experimental mode splitter. The straight curve represents the least square fit of (4) to the measured points, which are indicated by circles.

## IV. EXPERIMENT

An asymmetric $Y$-junction is designed using the procedures described in [3]. Its mode conversion factor (MCF, [4]) is relatively high (MCF = 2.6), which should result in a suppression of the unwanted mode of around 30 dB. The waveguides are made by diffusion of titanium in $X$-cut, $Y$-propagating lithium niobate. The branches of the output section are made from titanium stripes which are 90 nm thick and have widths of 4.3 and 5.7 $\mu$m, respectively. The branches of the input section are both 5 $\mu$m wide. The central bimodal waveguide is 10 $\mu$m wide. Five couplers are made with the length $L$ of the interference region increasing with steps of 0.5 mm. The diffusion is performed in a wet oxygen atmosphere (1 L $O_2$ per minute flowing through $H_2O$ of 70[°C]) at 1000[°C] for 16 h.

The couplers were characterized for TE-polarization by optical transmission measurement at 1319 nm. The transmitted powers $P_{11}$, $P_{12}$, $P_{21}$, and $P_{22}$ are determined and analyzed using (8). Each coupler delivers one point for the $G_N$-curve (Fig. 2), which yields the moduli of the matrix elements. It is found that the mode suppression is 29.2 dB, which is close to the theoretical value [4]. The splitting ratio of the symmetric $Y$-junction is 45/55, so there is a clear distinction in the behavior of the input and output sections. The coupling length found from the oscillation is 0.41 mm, which is in good agreement with the value of 0.31 mm from the effective index method [3]. The ratio of the attenuation factors for the output waveguides is for the best couplers close to one (within 20%), despite the fact that in the asymmetric $Y$-junction different waveguides and $S$-bends are used. This indicates that the modes are well guided, as is required for the measurement procedure to be valid. On the other hand, the values of this ratio for the couplers with apparent damages in the output waveguides imply an uncertainty in the suppression of at least 5 dB if the attenuation factors are not eliminated using (8). An analysis on the basis of experimental accuracy in the determination of $G_N$ gives an uncertainty of only 0.5 dB. This shows that our measurement procedure allows an accuracy in the determination of mode suppression, which would not be otherwise possible.

## V. CONCLUSIONS

An experimental procedure has been presented to characterize the mode splitting behavior of asymmetric $Y$-junctions. This procedure is based on interference of modes which are excited in a bimodal waveguide connected to an asymmetric $Y$-junction. Mode splitting is investigated by using different interaction lengths in the bimodal section. This section is connected to a symmetric $Y$-junction, which enables the determination of the relative phase of the interfering modes. From the oscillating curve found for the normalized coupled power versus the interaction length the mode suppression of the mode splitter can be accurately determined. The effect of bend losses, tapers, differences in fiber-chip coupling, damages and differences in propagation losses outside the coupling region, which all deteriorate the accuracy if a direct measurement of the mode splitting is made, can be eliminated. The suitability of our method is demonstrated with a mode splitter on lithium niobate, for which a mode suppression of 29.2 ± 0.5 dB is found.

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# Fabrication of $LiNbO_3$ Channel Waveguides Using Water

Yung-Sung Son, Hyung-Jae Lee, Yoon-Kyoo Jhee, Sang-Yung Shin, and Boo-Gyoun Kim

*Abstract*—**A channel waveguide in $LiNbO_3$ has been fabricated by using distilled water instead of acids for proton exchange and a self-aligned $SiO_2$ cap for diffusion. It thereby demonstrated that the water reaction is an important reaction to cause the index change in proton exchange.**

PROTON exchange (PE) in $LiNbO_3$ has been widely used as a complementary process or a viable alternative to titanium indiffusion for the fabrication of optical waveguides [1], [2]. PE takes place when the $LiNbO_3$ substrate is immersed in a proton source such as an acid or a hydrate melt (e.g., $Mg(NO_3)_2 \cdot 6H_2O$) at an appropriate temperature [1]. Jackel and Rice also reported that water impurities in melts of $AgNO_3$ or $TINO_3$ act as proton source [3]. Even though the benzoic acid [1] is the most popular proton source to fabricate low loss waveguides, there are reports on the fabrication of waveguides using other proton sources such as sulfuric [4], pyrophosphoric [5], and palmitic acids [6]. We report here fabrication of channel waveguides in $LiNbO_3$, by using distilled water instead of acids.

It is believed that the refractive index change of PE waveguides arises from the exchange between $Li^+$ and $H^+$. However, Loni *et al.* showed by using the hydrogen isotopic exchange technique that in unannealed PE waveguides the surface reaction also occurs between water molecules and $O^{2-}$ ions at the $LiNbO_3$ surface [7]. It means that in proton exchange two types of reactions such as acid reaction and water reaction may occur concurrently.

The commonly used $LiNbO_3$ crystal wafers are not a stoichiometric but a congruent (i.e., $(Li_2O)_\nu(Nb_2O_5)_{1-\nu}$ where $\nu = 0.486$) crystal. Thus, we may represent essential parts of reactions as follows. The acid reactions, commonly called the proton exchange, may be expressed as

$$Li_2O + H^+ \leftrightarrow LiOH + Li^+ \tag{1}$$

$$LiOH + H^+ \leftrightarrow H\text{-}O\text{-}H + Li^+. \tag{2}$$

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