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White-Light Spectral Analysis of Lithium Niobate Waveguides

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1. INTRODUCTION

Optical channel waveguides in lithium niobate are a very useful technique for building a variety of integrated optical components such as modulators, splitters, and frequency doublers. In many of these applications, single mode performance is essential in order to achieve the desired device performance. Determination of single-mode operation can be complicated by the fact that a multi-mode guide can support lower order modes and can appear single mode if the launch conditions for the light into the guide do not excite any of the higher order modes. Typical measurements often made to assure single-mode operation include optical mode spot imaging, and the "blink test". While these measurements are useful, they are strictly qualitative in nature, and thus do not provide the fine detail often desired in practice. In developing waveguide fabrication processes, it is more helpful to know how various process steps affect the wavelength at which the waveguide is single-mode, multi-mode and cut-off. In this paper, we show the usefulness of exciting waveguides with a broadband white-light source and observing the output of the guides over much of the visible and near IR spectrum with a spectrometer. Although this technique is not new, its usefulness in process development and control has not been emphasized¹.

2. EXPERIMENTAL SETUP

Figure 1 shows a block diagram of the white light spectrometer system. A tungsten-halogen lamp is coupled into and out of the waveguide under test by microscope objectives. The lenses which have a numerical aperture of 0.2 are achromatic and fairly well corrected in the visible and IR portions of the spectrum. In addition, a calibration trace is done to calibrate out variations of the lamp and optical system with wavelength. It should be noted that an ideal Gaussian spot when focused will only excite the lowest order mode. However, there is some coupling to the next highest order mode since the actual system is not a perfect Gaussian. The output light is then analyzed with a monochromator and a PIN diode detector. An ideal white light trace is shown in Figure 2. Assuming that the wavelength spans over the range of the lowest order mode and the next higher order mode, the ideal trace can be broken into four regions². In Region 1 both modes are far from cutoff and the ratio of light intensity at the output of the guide $I(\lambda, z_0)$ to the total available input light intensity $I_s(\lambda)$ can be described as:

$$I(\lambda, z_0)/I_s(\lambda) = K_{00}(\lambda) + K_{01}(\lambda) \quad (1)$$

where λ is the wavelength, z_0 is the length of the guide, and K_{00} and K_{01} are the input coupling coefficients for the lowest and next higher order modes, respectively. Region 2 describes the λ regime where the I_{01} cutoff is approached. In this case the ratio of output to input intensities is given by:

$$I(\lambda, z_0)/I_s(\lambda) = K_{00}(\lambda) + K_{01}(\lambda)\exp(-a_{01}(\lambda)z_0) \quad (2)$$

where a_{00} and a_{01} are the modal attenuation coefficients for the lowest order and next higher order modes, respectively. As the wavelength becomes longer the cutoff of the I_{01} mode is passed and region 3 covers the wavelength range where the I_{00} mode is still far from cutoff. This intensity ratio in this region is given as:

$$I(\lambda, z_0)/I_s(\lambda) \approx K_{00}(\lambda) \quad (3)$$

Finally as the I_{00} mode cutoff is approached in region 4, the intensity ratio is :

$$I(\lambda, z_0)/I_s(\lambda) \approx K_{00}(\lambda) \exp(-a_{00}(\lambda)z_0) \quad (4)$$

3. EXPERIMENTAL DATA

For this experiment a mask with straight guide dimensions of 2,3,4, and 5 μm was used to pattern channels in oxide on three-inch diameter x-cut lithium niobate wafers. These wafers were then proton exchanged in benzoic acid at 200°C and annealed at 350°C. Figure 3 shows a series of experimental traces corresponding to five different wafers processed at different times over a 12 month time period. These particular guides had a mask width of 3 μm and were exchanged for 10 minutes and annealed for 2 hours. The target wavelength for single mode operation of devices made with these guides was 830 nm. It is evident from Figures 2 and 3 that 830 nm is at the beginning of Region 3, just beyond the Region 2 edge for all five wafers. This wavelength corresponds to the tightest confinement of the lowest order mode and occurs just prior to the multimode region. The white light data provides a good measurement of the waveguide process control. For example, the slight variation in wavelength of the regions for the various wafers can be attributed to the degree of control in maintaining the mask linewidth in the masking oxide used on the wafer. Also shown in Figure 3 is a simulated trace assuming the following parameters:

$$\begin{aligned} a_0(\lambda) &= 5.2 \times 10^{-10} \times (\lambda - 1200) \text{ Nepers/nm} ; K_0(\lambda) = -.0202 + 2.0 \times 10^{-5} \times \lambda \\ a_1(\lambda) &= 2.1 \times 10^{-10} \times (\lambda - 775) \text{ Nepers/nm} ; K_1(\lambda) = 0.0128 - 8.0 \times 10^{-6} \times \lambda \end{aligned}$$

where as previously mentioned, a simple linear dependence with wavelength is assumed.

Another interesting way to present the white light data is shown in Figure 4. Here, the wavelengths for absolute single mode cut-off, well confined single mode operation, absolute second mode cutoff and well confined double mode are plotted vs. mask width dimension. By looking at the well confined single mode region, it is possible to select the proper mask width to use for a given wavelength of operation. It is apparent from this figure that the well confined single mode regime covers a broad spectrum (350 nm for the 3 μm guide). Experiments have also been conducted with devices under bias to observe the lowest $V\pi$ wavelength on a Mach Zehnder and the change in cut-off wavelength under bias on a phase modulator.

4. SUMMARY

We have shown the usefulness of exciting waveguides with a broad spectrum from a white-light source and measuring the guide response vs. wavelength. By proper interpretation of the various steps in these responses, it is possible to quantitatively determine cutoff, single mode operation, and multi-mode regimes and to monitor process variability over time. In conclusion, the white light excitation and spectral analysis technique is an important diagnostic for waveguide and device development in lithium niobate and any other optical waveguide material system.

1. J.E. Baran, Y. Silberberg, P. Perlmutter, "White-light characterization of integrated-optic waveguides and devices," OFC/IOOC, TUO2, 1987.
2. K.A.H. van Leeuwen and H.T. Nijhuis, "Measurement of higher-order mode attenuation in single-mode fibers: effective cutoff wavelength," Opt. Letters, 9, 252 (1984).

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Fig. 1 Experimental setup for exciting waveguides with white light: includes a tungsten-halogen lamp, microscope objectives, apertures, monochromator, and PIN diodes.

Fig. 2 a) Typical data for a lithium niobate waveguide scanned from 600 to 1700 nm
b) Ideal data showing four regions:
(1) I_{00} and I_{01} modes ; (2) I_{01} cutoff ; (3) I_{00} mode ; (4) I_{00} cutoff

Fig. 3 White-light spectrum for five non-simultaneously processed wafers with a target single-mode wavelength of 800 nm. Also shown is a simulated trace.

Fig. 4 Wavelengths of operation for single mode, multi-mode, and cutoff vs. mask dimensions for lithium niobate proton exchange guides fabricated with a 10 minute 200°C exchange and 2 hour 350°C anneal.

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