Recent advances in $LiNbO_3$ integrated optics

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Over the past several years, $LiNbO_3$ based integrated optics devices have moved from the device designer's laboratory into the more nearly real world of systems experiments. A few types of devices have even become commercially available in small quantities. Other articles in this issue will discuss the place of $LiNbO_3$ in experimental communication, sensing and computing systems, and the emergence of $LiNbO_3$ manufacturing and foundry services. This article discusses some of the theoretical and practical advances that are making $LiNbO_3$ a viable material.

When $LiNbO_3$ was seen as a material suited primarily for laboratory demonstrations of device concepts, problems such as device reproducibility or robustness were of little concern. Now that these devices are being manufactured, such apparently mundane issues take on great importance. This was recognized at a recent IEEE/LEOS Workshop on Integrated Optics, where four sessions addressed the questions: (1) Can you build what you design? (2) Can you design what you build? (3) Can you get the light in? and (4) How do you know what to build? These are precisely the questions that people designing, building, and using $LiNbO_3$ devices must ask — and answer — today. The answer to the last of these questions: "How do you know what to build?" obviously depends on what is to be done with the devices. Korotky, Bulmer, and Tanguay address some aspects of this question in related articles on applications of integrated optics. Here we consider advances in device reproducibility, modeling, and packaging.

Reproducibility

The question "Can you build what you design?" addresses the issue of reproducibility. One-of-a-kind devices can demonstrate a principle, but device reproducibility is necessary if those devices are to be used. Most $LiNbO_3$ devices today are made using titanium in diffusion. The properties of the guides and the devices made with them can be affected in a major way by minor differences in titanium stripe width, titanium thickness, diffusion temperature, and even the atmosphere in which the diffusion is carried out. The challenge is two-fold: to standardize (and optimize) fabrication conditions so that results are more nearly reproducible, and to design devices with minimal sensitivity to variations in fabrication conditions. One example of fabrication control is the technique of Voges, et al.[1] who perform diffusions in a closed platinum box. The box provides a clean, chemically inert surrounding and temperature homogeneity, leading to uniform and reproducible waveguides, which require no special treatment to prevent lithium outdiffusion. Similar improvements in fabrication have been made in many laboratories.

Fabrication insensitivity through device design is also being pursued at this time. Figure 1 shows an example of a new device that is relatively insensitive to variations in fabrication. This digital optical switch[2] will function properly so long as the angle at which the guides diverge is small enough and the difference in propagation constants for the two input guides is large enough. Along with reproducibility, this device offers polarization and wavelength insensitivity—important considerations for communications, since today's single-mode fibers scramble polarization and since there is increasing interest in wavelength-multiplexed systems.

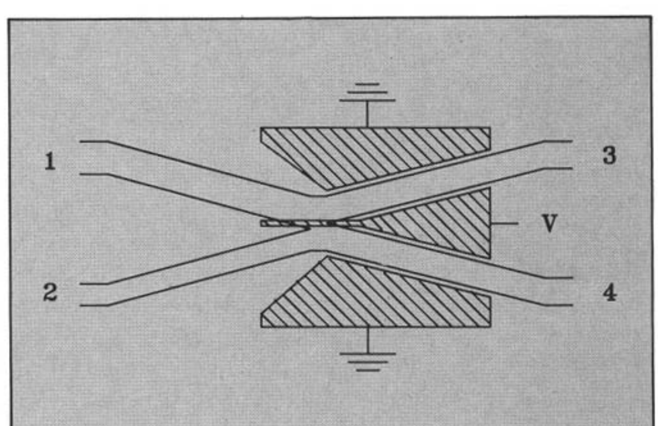

FIGURE 1. Schematic layout of a digital optical switch, with electrode pattern suitable for x-cut $LiNbO_3$. From Ref. 2.

Modeling

The question "Can you design what you build?" becomes more important as we look for devices performing more complicated functions and as the demands on device performance become greater. The coupled mode description of certain devices is a first order approximation, useful where the coupling between waveguides is fairly weak. Despite its limitations, coupled mode theory remains useful for modeling device performance and suggesting new device configurations. Coupled mode theory was used, for example, to design new devices, such as the non-symmetric interferometer[3] and the directional coupler with foreshortened electrode[4], both of which behave in ways that are intermediate between the better known directional coupler and the interferometer.

The beam propagation method[5], with its variants, provides a more sophisticated means of modeling device behavior, without the limitations of the coupled mode theory. Beam propagation calculations, based on early work that modeled propagation through the atmosphere, have been used to derive properties of waveguides, to calculate the strength of coupling between guides, and to predict device performance. The method, which is computation intensive, has found more use as faster and more powerful computers have become available. The power of the beam propagation method is illustrated in Fig. 2, which shows light propagating through a Mach-Zehnder interferometer. Figure 2a shows the device in the ON stage, and Fig. 2b shows a device turned off with an applied voltage. The excess loss for a device where the y-branch is too short (Fig. 2c) is dramatic. The calculations used to create these figures have led us to redesign devices to reduce loss.

Packaging

There are two major aspects to packaging of $LiNbO_3$ devices: optical and electrical. For optical communications, the question, "Can you get the light in?" should really be "Can you get light into the device from a single-mode fiber and then out of the device into another single-mode fiber, with minimum loss?" Doing so is possible only if both the device and its package have been designed to minimize loss.

One requirement for low-loss fiber-to-guide coupling is mode matching. If the guide mode has a size and shape different from that of the fiber, there will inevitably be loss. Normally, we expect the modes to be different because the fiber has radial symmetry, while the guide has a large index asymmetry imposed on it by the $LiNbO_3$/air interface. It has recently been shown that this asymmetry can be reduced by a second diffusion of magnesium. The

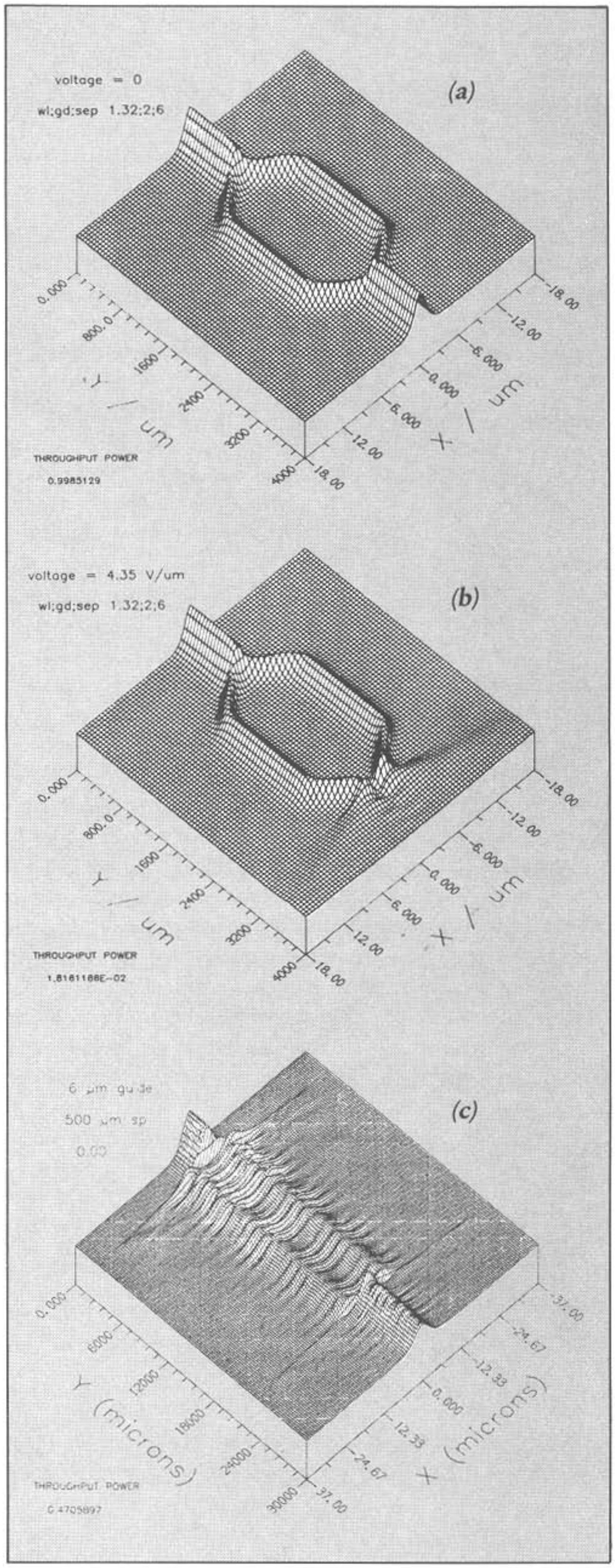

FIGURE 2. Simulation of Mach-Zehnder interferometer operation, made using beam propagation method. (a) No applied voltage: device is "ON" (b) With applied voltage: device is "OFF" (c) With no applied voltage, but too short y-branch: device is "ON" but suffers >3dB loss. Simulations provided by R.J. Hawkins.

magnesium lowers the refractive index, effectively burying the guide and symmetrizing it. In addition, losses due to surface scattering are reduced, since the optical field is no longer at the $LiNbO_3$/air interface. Further reduction of losses has been achieved by using AR coatings to eliminate Fresnel reflections. AR coatings have a function more important than loss reduction—they reduce reflections back into the source, which is important because these reflections can have catastrophic consequences for coherent systems. Problems caused by reflections can also be avoided by polishing the crystal ends at a slight angle. This does not eliminate the reflection, but prevents its entering the input fiber.

As $LiNbO_3$ devices are pushed to higher speeds, the electrical aspects of device design and packaging become as important as the optical. The fastest $LiNbO_3$ devices to date have been those with traveling wave electrodes, such as the 40 GHz modulator recently reported by Korotky.[4] Because the optical and modulating microwave fields travel at different speeds in $LiNbO_3$, the maximum modulation frequency available with simple traveling wave electrodes is inversely proportional to electrode length. The 40 GHz speed was possible only with short (0.25 cm) electrodes, and therefore required a large modulating voltage. If this kind of electrode is used, increasing speeds are possible only with even shorter electrodes and therefore require even greater voltage. Further increases in the maximum speed of $LiNbO_3$ devices have been made by using electrodes with aperiodic phase-reversed electrodes[6], but ultimately, the speed is limited by the breakdown voltage for $LiNbO_3$.

In practice, more down-to-earth considerations can place limits on device speeds. For example, even the electrode with the fastest potential response will not produce a fast device if the package itself prevents voltage from reaching the device. No single solution to this problem has appeared, but most high speed devices have electrodes designed to be impedance matched to the microwave source and tapered to match connector dimensions, both of these to prevent microwave reflection losses. High speed devices also use packages designed to prevent propagation of unwanted microwave modes.

The tremendous improvements in $LiNbO_3$ technology in the past few years has fed upon both theoretical and experimental advances, a few of which have been described here. Further developments will require, in addition, some very practical engineering work.

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The role of silicon in integrated optics

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Silicon is the mainstay of the modern microelectronics industry, so it is only natural to consider its potential for use in integrated optical or optoelectronic circuits. This idea is especially attractive from a commercial point of view, since high purity crystalline silicon is already available at low cost, and since there is already a well established processing technology for silicon.

Early attempts to define a silicon-based technology for integrated optics met with only limited success. Though silicon is in many ways an ideal material for electronics, it