Linearized electrooptic directional coupler modulator in stoichiometric lithium niobate

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ABSTRACT

This paper reports on a novel optical linearized directional coupler modulator in stoichiometric lithium niobate (SLN). The linearized design has important applications in analog and RF communications systems where fiber optic link performance depends critically on the spurious-free dynamic range of the modulator. Newly available SLN has several distinct advantages over the congruently grown crystals commonly used for high speed integrated optic devices, including higher electrooptic coefficient and better ferroelectric properties. The higher electrooptic coefficient yields lower drive voltage, while the enhanced ferroelectric properties enable better velocity-matched electrode structures using domain inverted waveguides. This paper addresses the operation of the linearized directional coupler design, and the critical advantages of the SLN substrate for implementing high-speed operation using velocity-matching.

Keywords: linearized modulator, stoichiometric lithium niobate, electrooptics, directional coupler, Mach-Zehnder

1. INTRODUCTION

Optical modulators with linearized response functions have been investigated for many years[1,2] due to their important applications in analog and RF communications and data transfer links. In particular, a linearized response function offers higher dynamic range because of lower harmonic and intermodulation distortions. Another advantage of a linearized response function is an enhanced tolerance to bias point drift. In evaluating the merit of a linearized design from a systems application perspective, the slope efficiency, defined as the change in intensity per unit change in modulator drive voltage at the operating point, is an important figure of merit. This quantity depends not only on the shape of the response function, but also scales with the insertion loss, which acts as an overall multiplicative factor.

Recently, developments in linearized directional coupler modulator design have yielded encouraging results that promise high linearity and high slope efficiency for analog and RF communications applications.[3] These designs rely on a coupling coefficient which varies along the length of the coupler. These designs are synthesized based on the small-coupling limit, where a Fourier conjugate relationship exists between the coupling and response functions. Various synthesis techniques have been developed[4] which first apply an inverse Fourier transform to the desired response function to determine an approximate coupling function and then iterate the design until the desired response function is achieved. In particular, the ideal response function has very linear, very steep transition, as shown in Figure 1.

Achieving the goal of state-of-the-art modulator performance requires not only innovative optical circuit designs, but innovative materials systems and processing techniques. Recently, a new form of lithium niobate ($LiNbO_3$, or LN) has become available, stoichiometric lithium niobate (SLN), which has better nonlinear, electrooptic, and ferroelectric properties than the commonly produced congruent lithium niobate (CLN). In this paper we outline our current research program that is implementing new linearized directional coupler designs on the new material SLN.

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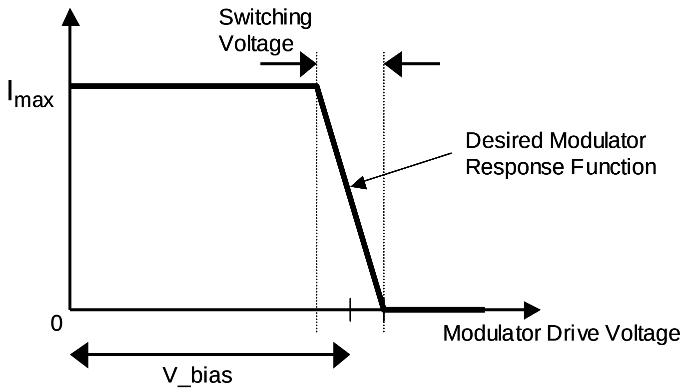

Figure 1: The ideal response function of an optical modulator would be very steep and linear.

2. ADVANTAGES OF STOICHIOMETRIC LITHIUM NIOBATE

Today lithium niobate (LN) is the preferred substrate for electrooptic devices such as high-speed modulators and switches. This remarkable material is expected to remain the preferred substrate for these applications, while expanding into a variety of new application areas such as nonlinear optical generation, advanced modulation formats, optical packet switching, wavelength conversion, and holographic storage. Optoelectronic integration with high-speed electronics using GaN epitaxial layers on LN is an important example of recent advances in materials and devices that promise continued dominance of LN in a variety of applications. The recent availability of stoichiometric lithium niobate (SLN), with a host of enhanced properties, promises somewhat of a renaissance in the world of LN applications.

Lithium niobate is normally produced by pulling crystals from a melt with a Nb to Li mole ratio of 51.5% to 48.5%. This composition, called the congruent composition, has been preferred because this is the composition which the solid coexists with a single phase melt. Congruent lithium niobate (CLN) is thus the substrate used for all commercially available optical waveguide products today. The off-stoichiometric composition, while convenient for crystal growth, has several well-documented disadvantages relative to SLN. The advantages of SLN over CLN include:[5]

- Increased nonlinear coefficient (44.3 pm/V vs. 34.1 pm/V), which translates directly into an increased electrooptic coefficient (38.3 pm/V vs. 31.5 pm/V)
- Better high optical power handling characteristics[6] (lower Mg doping percentage, 1% vs. 5% for 1 MW/cm^2 power handling capability at 532nm)
- Enhanced ferroelectric properties (higher ferroelectric Curie temperature, and lower coercive field for domain inversion)
- Greater optical transparency range (UV band edge at 305 nm vs. 325 nm)

These enhanced electrooptic and ferroelectric properties arise naturally from the lower intrinsic defect density in the lattice at the stoichiometric composition. In the congruent crystal structure, excess Nb ions occupy Li sites, with charge compensation achieved either by Nb or Li vacancies, or both[7].

One area where SLN offers critical advantages to this design is in high-speed operation where velocity matching between the optical field and the electrical drive is required.[8] SLN can be used to enable better velocity matching in directional couplers because patterned ferroelectric domain inversion is much more practical in SLN than in CLN. For example, the lower coercive field (<4 kV/mm vs. 21 kV/mm) allows for room temperature poling using lower field strength, with greatly increased process yield. And the higher Curie temperature makes the poled domains resistant to subsequent processing steps, notably Ti indiffusion at ~1000° C. The use of an inverted ferroelectric domain on one leg of the directional coupler creates opposite sign electrooptic coefficient in the two coupler legs, allowing for push-pull operation with a single electrode over both waveguides. This enables the proper width-to-gap ratio for velocity and impedance matching the electrodes, in contrast to the usual directional coupler case, where velocity matching designs are difficult to achieve.

The linearized modulator designs are based on the directional coupler optical circuit. Evanescent coupling between two adjacent waveguides provides a periodic exchange of energy between the two waveguide channels. Because the decay of the modal field away from the center of the waveguide is exponential, the coupling length is very sensitive to changes in the gap between the waveguides and the modal field profile. For proper operation the coupling region must be precisely half the coupling length. Therefore, fabrication tolerances are critical, influencing the manufacturing yield of directional coupler-based devices such as modulators and 2x2 optical switches. Reduced diffusion rates in SLN offer the possibility of greater process control, with the associated increase in manufacturing yield.

Diffused optical waveguide production is SLN is a new area, with very little reported in the current literature. Nakajima et. al.[9] find that longer diffusion times are required for Ti waveguide production relative to standard SLN recipes. They also report a more nearly isotropic diffusion, in contrast to CLN where the diffusion coefficient in the z direction is known to be larger than that in the x (or y) direction. Caccavale et. al.[10] report similar findings in a study of Ti diffused slab waveguides probed by secondary ion mass spectroscopy (SIMS). The smaller diffusion coefficients found in these studies are in agreement with our results on Ti diffused waveguide production. We have fabricated Ti diffused waveguides using proprietary recipes and processing technology, and we have observed waveguides with losses ranging from 0.2 – 1.0 dB/cm. This is suitable for device fabrication. Fabrication of proton exchanged slab and channel waveguides in SLN is also an active area of research, and our results indicate increased diffusion times for waveguide production relative to CLN.

3. LINEARIZED DIRECTIONAL COUPLER DESIGNS

The basis of directional coupler response function engineering was originally developed by Alferness[11] who pointed out that for a standard uniform coupler the response function was a sinc^2 function, which is the Fourier transform of the rectangular coupling function (i.e., zero everywhere except a constant value over the coupling length). This observation applies in the weak coupling limit, and the inverse Fourier transform applied to a desirable transfer function of choice (see Figure 1) thus yields an approximation to the appropriate coupling function that would yield this transfer function. For the more realistic case where weak coupling cannot be assumed, various techniques[4] have been developed to iteratively refine the coupling function by repeatedly recalculating the transfer function of the trial coupling function.

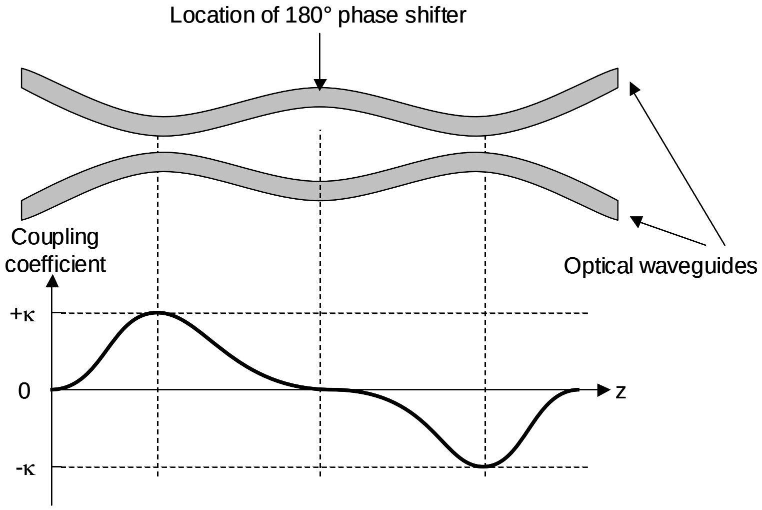

Figure 2: Schematic example showing both magnitude and sign changes in the coupling function.

In coupled mode theory, and in the linearized design algorithms discussed above, the coupling function is complex valued. The local coupling coefficient can take on positive or negative values, or have imaginary component. The interpretation of negative or complex coupling coefficient is not obvious. A simple geometrical interpretation of the coupling coefficient κ stems from the relationship $\kappa = \pi/2L_c$ where L_c is the coupling length over which power is completely transferred from one waveguide to the other. The key to understanding negative and imaginary coupling coefficients lies with the relative phase of the advancing optical modes in the two waveguides: a 180° relative phase change between the phases in the two waveguides is interpreted as a sign change in κ. Similarly, a 90° relative phase imparts an imaginary coupling constant.

Figure 2 shows an example of a coupling function showing both magnitude and sign changes. Magnitude changes are implemented by varying the waveguide spacing. The sign change is implemented by adding a feature that introduces a 180° phase shift between the two legs.

Implementing a general synthesized coupling function would require precise control over both the magnitude and phase of the local coupling coefficient. This presents a great challenge to fabrication technology. We have devised a coupling function that considerably simplifies the fabrication, yet offers suitable linearization to be of great value in analog and RF fiber optic links. In this design the magnitude of the coupling coefficient is constant over the length of the coupling region, and phase control is limited to four identical phase shifters, each providing a 180° phase shift and thus reversing the sign of the coupling coefficient. We refer to this as the “Pi Phase Shift” design, as shown in Figure 3.

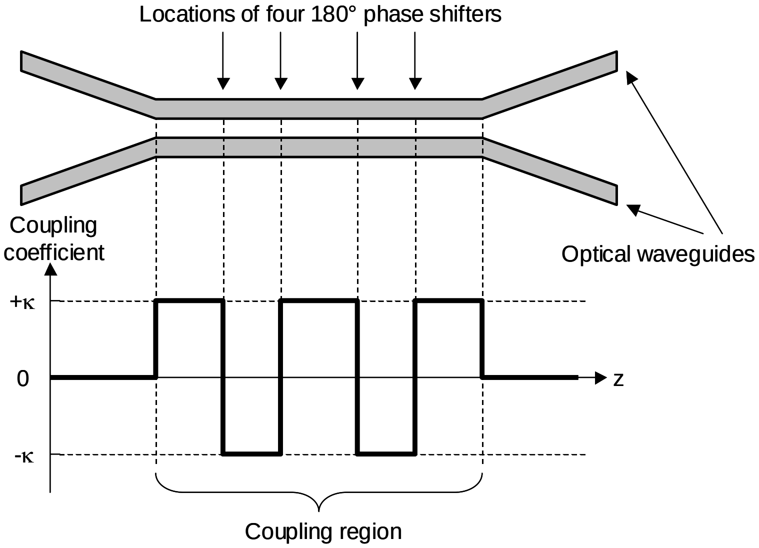

Figure 3: Schematic directional coupler and coupling function for a device fabricated with the Pi-phase shift design.

The operation of the Pi phase shift design is modeled using transfer matrices from coupled mode theory. Figure 4 illustrates the behavior of the Pi phase shift design (lower graphs) compared to the standard directional coupler (upper graphs). Shown on the left is the evolution of the optical fields in the two waveguides as a function of distance along the coupler. Multiple curves are shown corresponding to increasing drive voltage. In the standard directional coupler, no applied voltage results in a complete power exchange between the two waveguides. Increasing the drive voltage both shortens the period and lowers the magnitude of the exchange. At the switching voltage (the largest voltage pictured), the input light returns to the original waveguide by the end of the device. At the right is shown the corresponding transfer function.

In contrast, the Pi phase shift design (lower graphs) shows the effect of the 180° phase shifters on the power transfer. Again, multiple curves are shown corresponding to increasing drive voltage. In each case, the evolution follows a fixed periodicity (due to fixed magnitude coupling coefficient) punctuated by abrupt reversals at the locations of the phase shifters. At right is the corresponding response function plotted with drive voltages corresponding to the individual curves at the left. The linearization of the response function is evident even when plotted with just a few data points, as shown.

Note that in the Pi phase shift design of Figure 4 the slope efficiency is about the same as the standard directional coupler design. We believe this is an inherent limitation due to the simplifications of the Pi phase shift design.

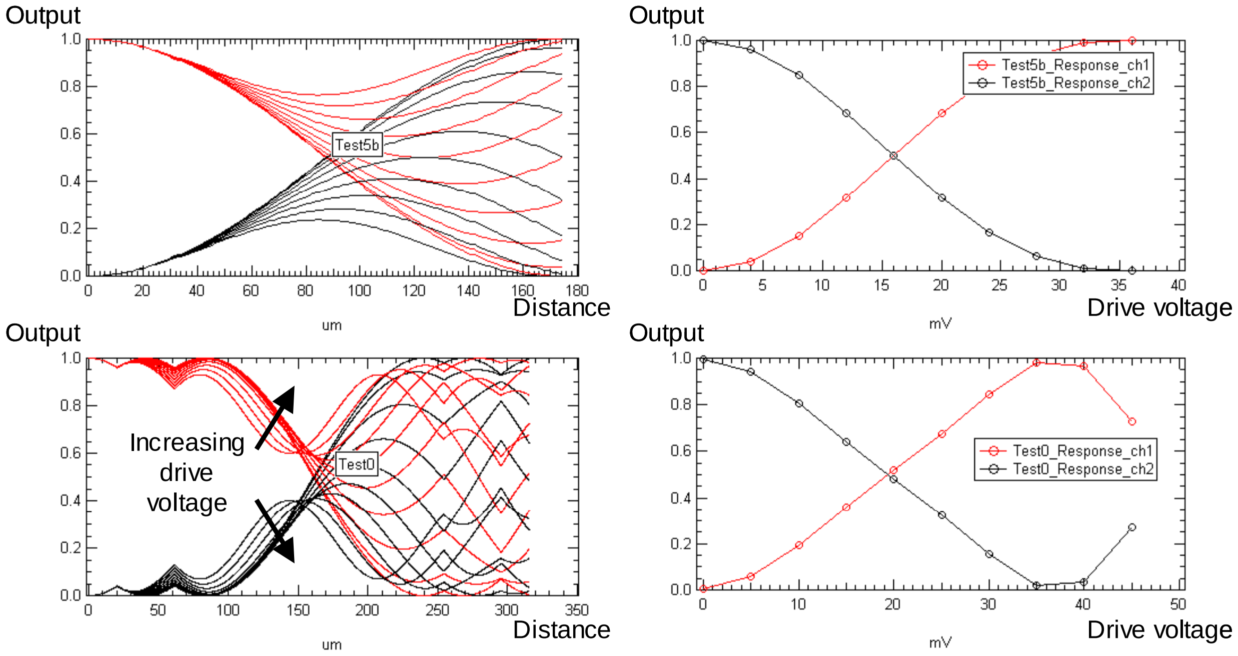

Figure 4: Simulations comparing the standard directional coupler (upper figures) to the linearized Pi-phase shift modulator design (lower figures).

The best way to quantify the linearity of the response function is to plot the magnitude of the intermodulation distortion (IMD) and harmonic distortion terms, using a simple two-tone model as a function of bias point. The second-order IMD term is applicable only in the case where the bandwidth of the RF carriers exceeds one octave, and may or may not be of importance in a particular application. IMD3 terms, the third order IMD products, however are always of importance, as are harmonic distortion terms. Our results show a variety of potential Pi phase shift designs, with varying placement of the phase shifters yielding various degrees of linearity and various degrees of tolerance to fabrication errors. Our current fabrication efforts are aimed at the design that gives a balance between linearity and fabrication intolerance.

Figures 5 and 6 below show the results of transfer matrix calculations that illustrate the fabrication tolerances due to errors in the coupling coefficient and phase shift of the phase shifters. Fabrication errors in the coupling coefficient result from variations in waveguide formation or from very small lithographic errors in the coupling region. Errors in the phase shift of the phase shifters are expected to result from variations in the processes used to incrementally change the effective propagation index in the phase shift segments. Added insertion losses of the phase shifters due to modal mismatch between the unperturbed and perturbed index profile have been simulated using a 3D beam propagation[12] technique and are expected to be minimal (<0.1 dB each).

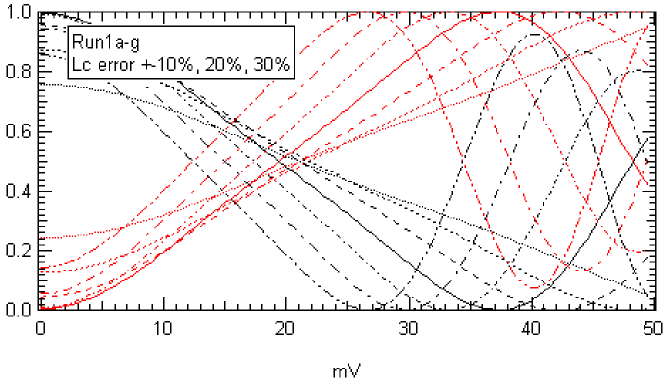

Figure 5: Response functions in which the coupling length L_c has been varied ±10%, 20% and 30% from the ideal coupling length. Linearity of the response function does not suffer greatly.

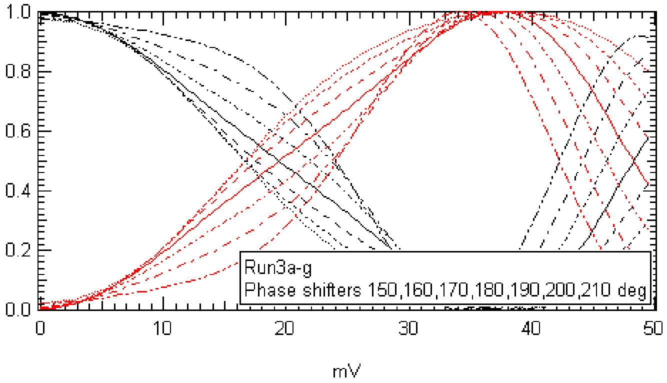

Figure 6: Response functions in which the phase shift has been varied over the range 150° to 210° in 10° increment. Linearity of the response function is clearly sensitively dependent on the fabrication accuracy of the phase shifter.

4. CONCLUSIONS

This paper has presented an overview of a research program that combines novel linearized coupler designs with the use of a new electrooptic substrate, stoichiometric lithium niobate (SLN). Waveguide production recipes have been developed in SLN that yield low loss waveguides suitable for device fabrication. The simplified Pi phase shift linearized coupler model is presented, and is found to be a highly linear design optimized for fabrication intolerance of phase shifts. Other designs with equally good linearity and larger slope efficiency, however require control over both the phase and magnitude of the local coupling coefficient. Current fabrication efforts therefore are focused on the Pi phase shift design.

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