40 Ghz Electro-optic Polarization Modulator for Fiber Optic Communications Systems

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ABSTRACT

A novel ultrahigh-speed electro-optic polarization modulator is introduced. The modulator uses a mode converter and a static polarization controller to change the output polarization state in a circular path, following a great circle, around the Poincaré sphere. Any two states on the Poincaré sphere can be connected. The mode converter is constructed using an AlGaAs ridge waveguide combined with slow-wave travelling wave electrodes. The travelling wave electrodes are designed to match the velocity of the electrical modulating signal, the data signal, to the optical carrier signal over a broad frequency range. This modulator demonstrates a 3 dB bandwidth in excess of 40 GHz. The polarization modulator exhibits extremely low differential group delay, on the order of a few 10s of femto-seconds, and low drive voltage, on the order of 5 V.

Keywords: Modulator, electro-optic, 40 Gb/s, polarization modulation, Gallium Arsenide

1. INTRODUCTION

Traditionally, optical data transmission has relied heavily on on-off keying to encode data onto an optical carrier signal.[1] Recently, there has been increasing interest in alternative modulation formats using polarization modulation.[2,3,4] In this paper, we present a novel ultrahigh-speed electro-optic polarization modulator. The modulator uses a mode converter in combination with a polarization controller to change the output polarization state in a circular path around the Poincaré sphere. The mode converter is constructed using an AlGaAs ridge waveguide combined with travelling wave electrodes.[5,6] The travelling wave electrodes are designed to match the velocity of the electrical data signal to the optical carrier signal over a broad frequency range. This modulator demonstrates a 3 dB bandwidth exceeding 40 GHz combined with extremely low differential group delay and low drive voltage. The design and performance characteristics of the modulator are analyzed and discussed. A recent experiment, demonstrating a dramatic reduction in the bit error rate in a 43.5 Gb/s RZ-DPSK system transmitting over 200 km spans by using the polarization modulator to change the polarization state of alternate bits,[2] is reviewed. Finally, other applications of the polarization modulator are presented.

In addition to this introduction, this paper is divided into 4 sections. In Section 2 we discuss the operation of the polarization modulator from both an optical and an electrical perspective as well as some of the benefits offered by it. In Section 3 we present results of optical measurements made on the polarization modulator. In Section 4 we discuss possible applications of the polarization modulator. In Section 5 we summarize the paper and present conclusions.

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2. PRINCIPLES OF OPERATION AND BENEFITS

2.1 Principles of operation - optical

Our electro-optic polarization modulator uses a single waveguide mode converter to switch light between polarization states that lie on the great circle of the Poincaré sphere that contains the horizontal linear polarization state (the H state), the vertical linear polarization state (the V state), and the two poles (the right-handed and the left-handed circular polarization states, the R and L states, respectively), the HRVL circle, see Figure 1. This single waveguide mode converter is a "two-moded" AlGaAs/GaAs waveguide fabricated in (100) GaAs and running in a $<01\bar{1}>$ direction. The waveguide is two-moded in that it supports two orthogonal eigen-modes. Light is launched into one facet of the waveguide in either the H state, corresponding to the fundamental TE-like mode, or the V state, corresponding to the fundamental TM-like mode. This launched, linearly polarized, light is resolved into two components each of which corresponds to one of the eigen-modes of the waveguide. By design, these two eigen-modes are linearly polarized at 45^{o} to the horizontal and the vertical directions and correspond to the D and D' states in Figure 1.

Essentially our polarization modulator is as a TE↔TM mode converter followed by a "static" polarization controller. The TE↔TM mode converter operates in the following manner. Figure 2 shows a cross section of the AlGaAs/GaAs waveguide together with the crystal orientation. Application of an electric field in a $<011>$ direction induces changes

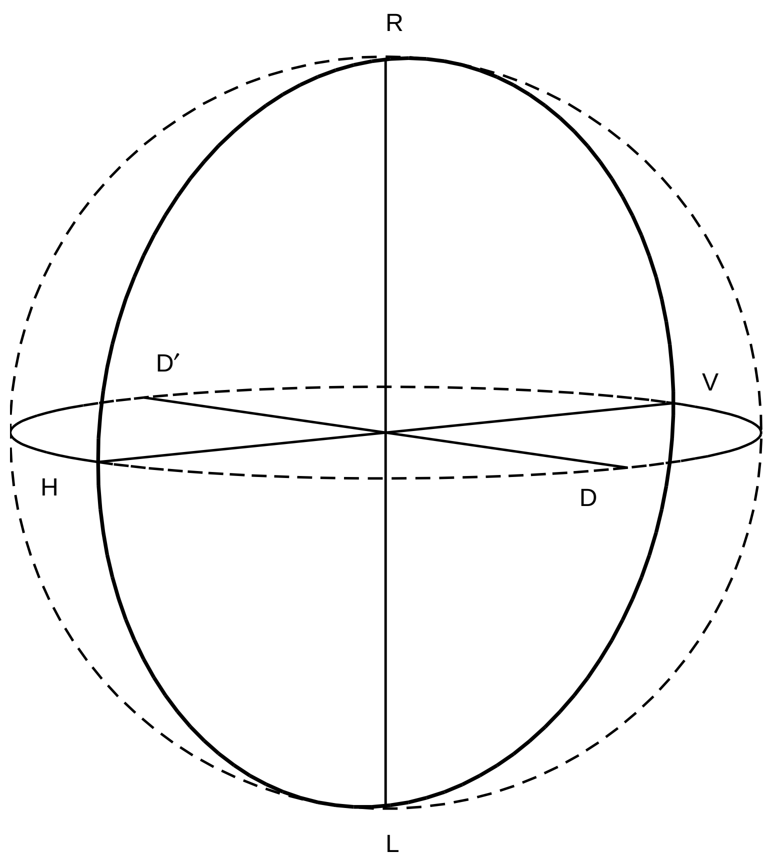

Figure 1. 3-D perspective view of the Poincaré sphere showing several special polarization states. The H and V points correspond to horizontal and vertical linear polarizations. The R and L points correspond to right and left circularly polarized light. The D and D' points correspond to linearly polarized light at ±45 degrees to the horizontal. The HRVL circle is emphasised.

in the optical indicatrix along the $<\sqrt{2}11>$ and $<\sqrt{2}\bar{1}\bar{1}>$ directions via the electro-optic effect. These changes are equal but opposite. If, say, light in the H state, i.e., the TE-like mode polarized parallel the $[011]$ direction, is launched into the waveguide it will resolve itself into the D and D' states, the hybrid eigen-modes polarized in the $[\sqrt{2}11]$ and the $[\sqrt{2}\bar{1}\bar{1}]$ directions. Since in our modulator the differential modal loss of the hybrid eigen-modes is low, the polarization state at the output will move along the great circle passing through the poles as the applied electric field changes. In the conversion from TE to TM, or visa versa, the polarization state moves along the great circle of the Poincaré sphere that connects the two points, H and V, on the equator of the sphere through one of the poles, depending on the direction of the applied field. Using the polarization modulator, ultrahigh-speed modulation between any two states on the Poincaré sphere can be achieved.

2.2 Principles of operation – electrical

In order to achieve ultrahigh-speed operation the velocity of the modulating electrical signal must be matched to that of the optical signal and the resistive losses must be kept to a minimum. The velocity of the modulating electrical signal is matched to that of the optical signal by loading the transmission line with fins and pads,[5,6] see Figure 3. The fins and pads add capacitance to the line, without creating a significant change in the inductance, which results in a lower phase velocity or higher microwave index. The microwave index is tailored to be the same as the group index of the optical waveguide at the upper 3 dB point of the modulator. Figure 4 shows the microwave-wave index of a capacitively loaded, "slow-wave" transmission line as a function of frequency. The optical group index is also shown and is invariant with the microwave frequency. The fins and pads also reduce the resistive losses, since without them the current density in the "rail sections" would be much higher for comparable electrode gaps at the ridge.

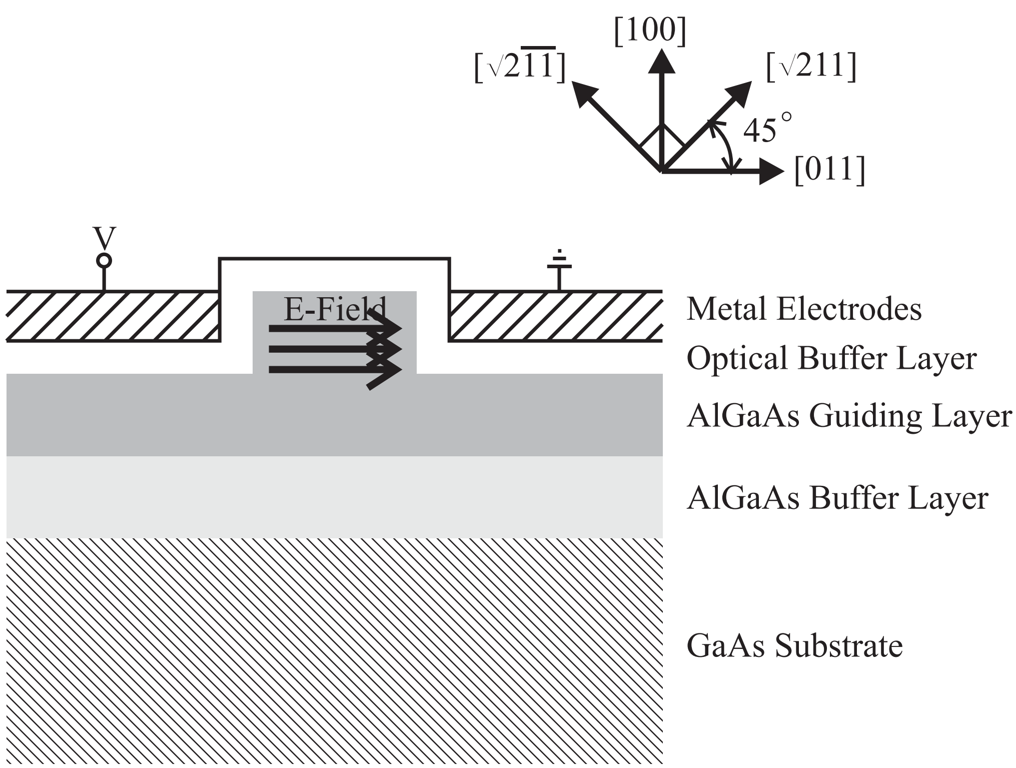

Figure 2. Cross-section of the AlGaAs/GaAs waveguide together with the crystal orientation.

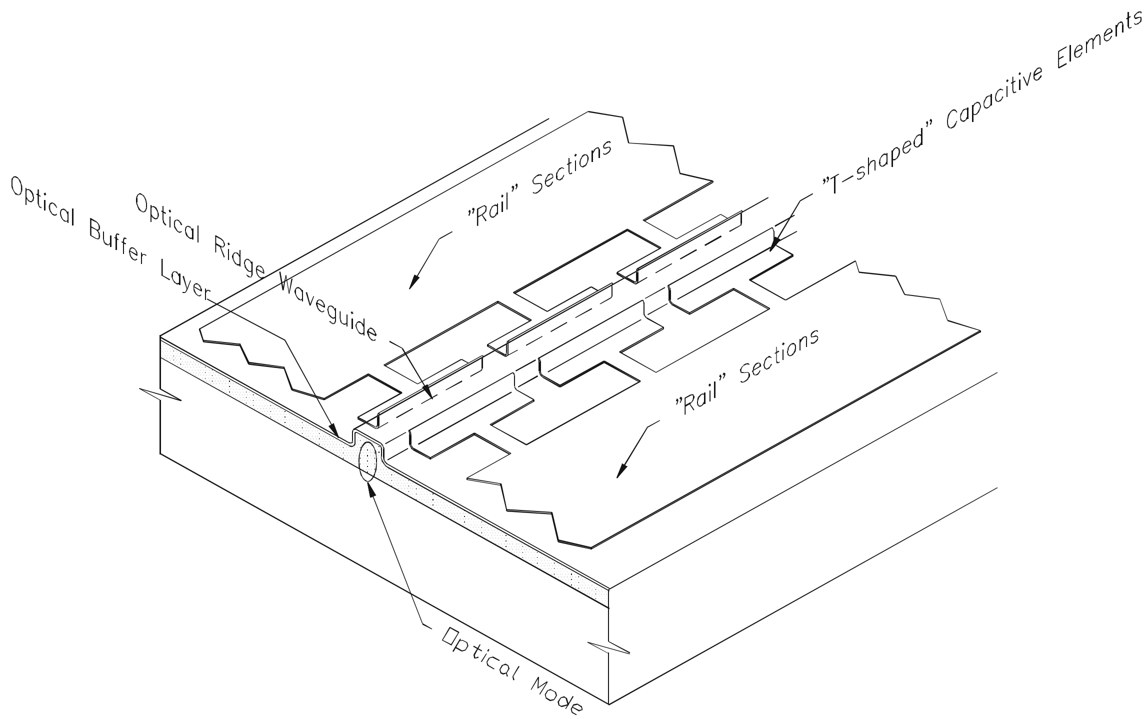

Figure 3. Capacitively loaded, slow-wave transmission line for matching the modulating signal's velocity to that of the optical signal. The fins and pads form the "T-shaped" capacitive elements.

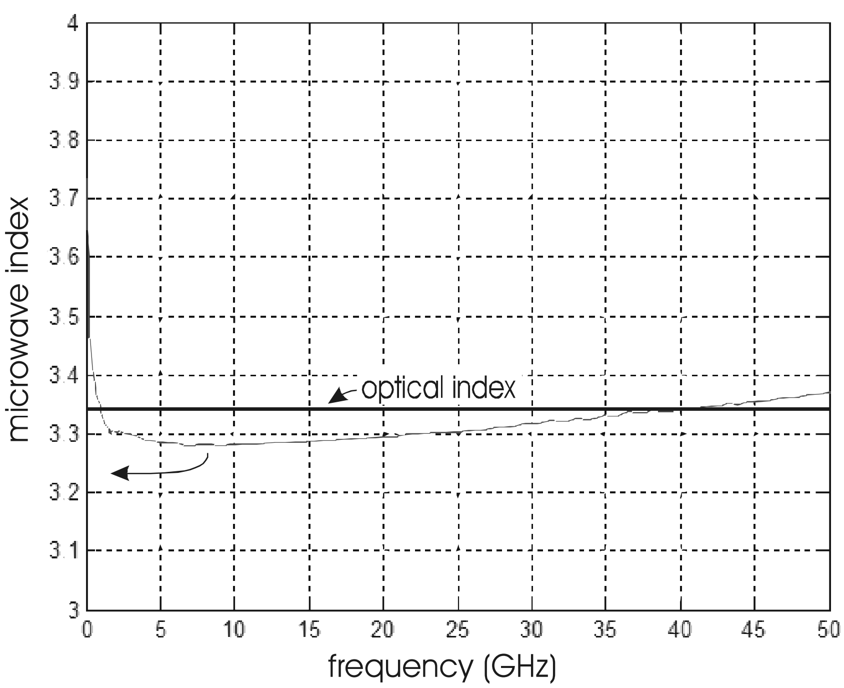

Figure 4. Microwave index as a function of frequency. The microwave index of the structure is tailored to be the same as the optical index at the modulator's 3 dB point, here at approximately 40 GHz.

2.3 Benefits over existing polarization converters

There are three principal benefits of our polarization modulator over existing polarization converters. These are ultrahigh-speed operation, low drive voltage, and low differential group delay (DGD).

Figures 5 and 6 show the frequency response of one of our polarization modulators; Figure 5 shows $|S_{21}|$ and 6 shows $|S_{11}|$. Here the modulator is being operated between the H and V states on the HRVL circle. The 3 dB frequency is that frequency at which the signal is 3 dB down after being passed through an analyzer (linear polarizer) aligned with the V state; in this case it is ~46 GHz. The drive voltage of the polarization modulator is the voltage needed to drive the modulator between two orthogonal polarizations states. For a 40 Gb/s bit rate, the drive voltage is typically 5.5 V.

Another aspect of our polarization modulator that contributes to its ultrahigh-speed performance is that the modulator produces minimal phase modulation. When the modulating electric field is oriented as indicated in Figure 2, there is no net phase modulation for the device since the electric field results in a “push-pull” effect between the two hybrid eigen-modes.

Low DGD results from the symmetry of the two hybrid eigen-modes. With proper design and fabrication, both modes “see” essentially the same structure and as a result have nearly the same velocity and differential loss. The main contribution to the DGD is the waveguide birefringence. For efficient mode conversion, the waveguide birefringence needs to be very small. Since GaAs is optically isotropic in the absence of an electric field, the waveguide birefringence is dominated by geometric birefringence and is on the order of 1E-4. For typical waveguide lengths of a few centimetres, the DGD is expected to be on the order of 10’s of femto-seconds. In comparison, an X or Y-propagating lithium niobate phase modulator is expected to have a differential group delay between 10 and 15 ps due to a

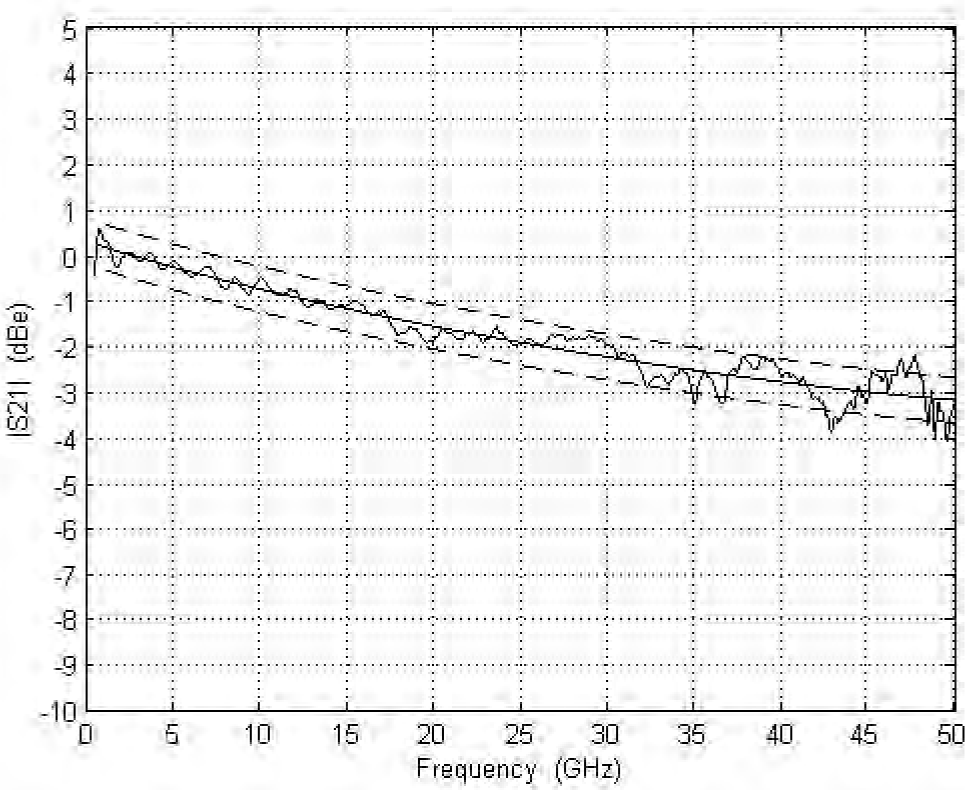

Figure 5. $|S_{21}|$ for one of our modulators; a polynomial fit has been used to determine the 3 dB point of ~46GHz.

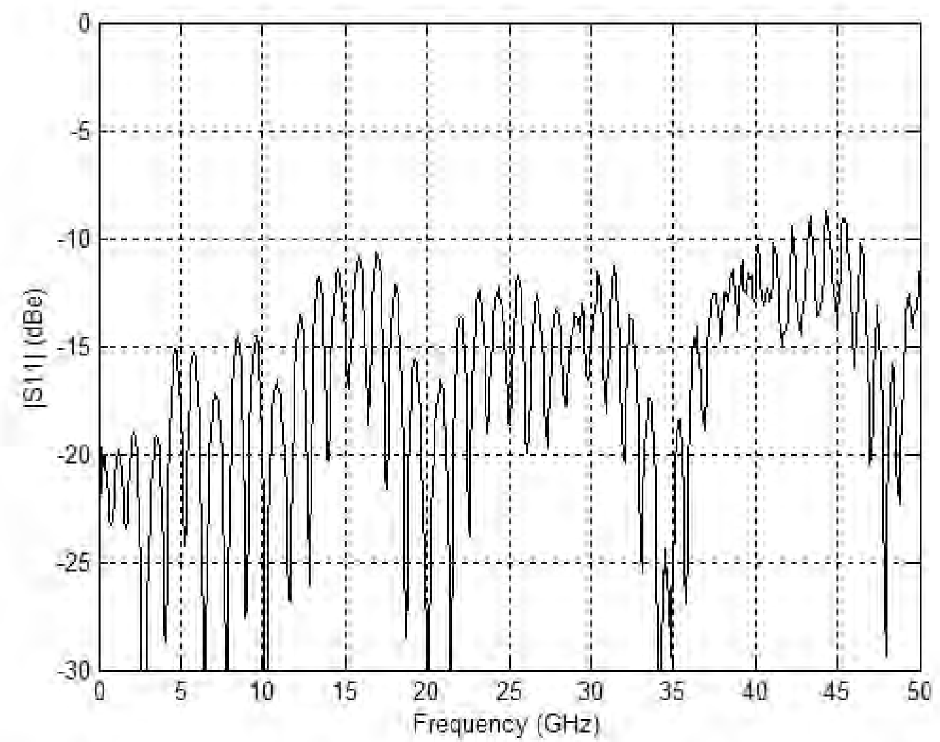

Figure 6. $|S_{11}|$ for the modulator of Figure 5. It shows better than 11 dB return loss up to 40 GHz.

material birefringence of approximately 0.07[7] at 1550 nm. A delay of 10 ps represents an unacceptably large portion of the 25 ps bit period of a 40 Gb/s data stream. In our modulator, a 25 ps pulse can enter the waveguide and suffer negligible DGD distortion upon exiting the device.

By being ultrahigh-speed, our polarization converter can be used in advanced modulation schemes requiring that the polarization of the data rapidly change from one state to another. Some such schemes are discussed in Section 4 below.

3. POLARIZATION MEASUREMENTS

We now present Stokes vector measurements for our modulator, plotted on the Poincaré sphere. Figure 7 shows experimental data as the modulator is swept through twice the drive voltage. Figure 7a is a 3-D perspective view showing that the output states pass very near the H, R, V and L points in the Poincaré sphere on the HRVL circle. Figures 7b, c and d show the same data projected into the S3, S2, and S1 normal planes, respectively. Through examination of Figures 7b and d, it is evident that the output states of the polarization modulator deviate slightly from the ideal HRVL circle. One way to quantify this deviation is to examine the orthogonality of output states of the modulator. On the Poincaré sphere, two orthogonal states are co-linear and point in opposite directions, or alternatively, have a dot product equal to -1. The ideal polarization modulator traces a great circle on the Poincaré sphere; each point along the transfer function has a perfectly orthogonal counterpart. The measured orthogonality between states in our polarization modulator is shown in Figure 8. The orthogonality is calculated at each output state, $\mathbf{P}_1$, of the modulator according to

$$ER = -10\log\left(\frac{1 + P_1 \bullet P_2}{2}\right)$$

where $\mathbf{P}_2$ is the output state that minimizes the dot product with $\mathbf{P}_1$.

In Figure 8, the output states of the modulator are identified on the x-axis by the angle the Stokes vector makes with the S1 axis of the Poincaré sphere, shown as the angle θ in Figure 7c. Since all of the output states nominally lie in the S1-S3 plane, this single angle is sufficient to identify each output state. Figure 8 shows that the extinction ratio is in excess of 28 dB for all of the polarization output states and even greater than that amount for a subset of the operating points. These results indicate that the device is capable of producing a set of highly orthogonal states and that the extinction ratio can be maximized by choosing the appropriate operating point.

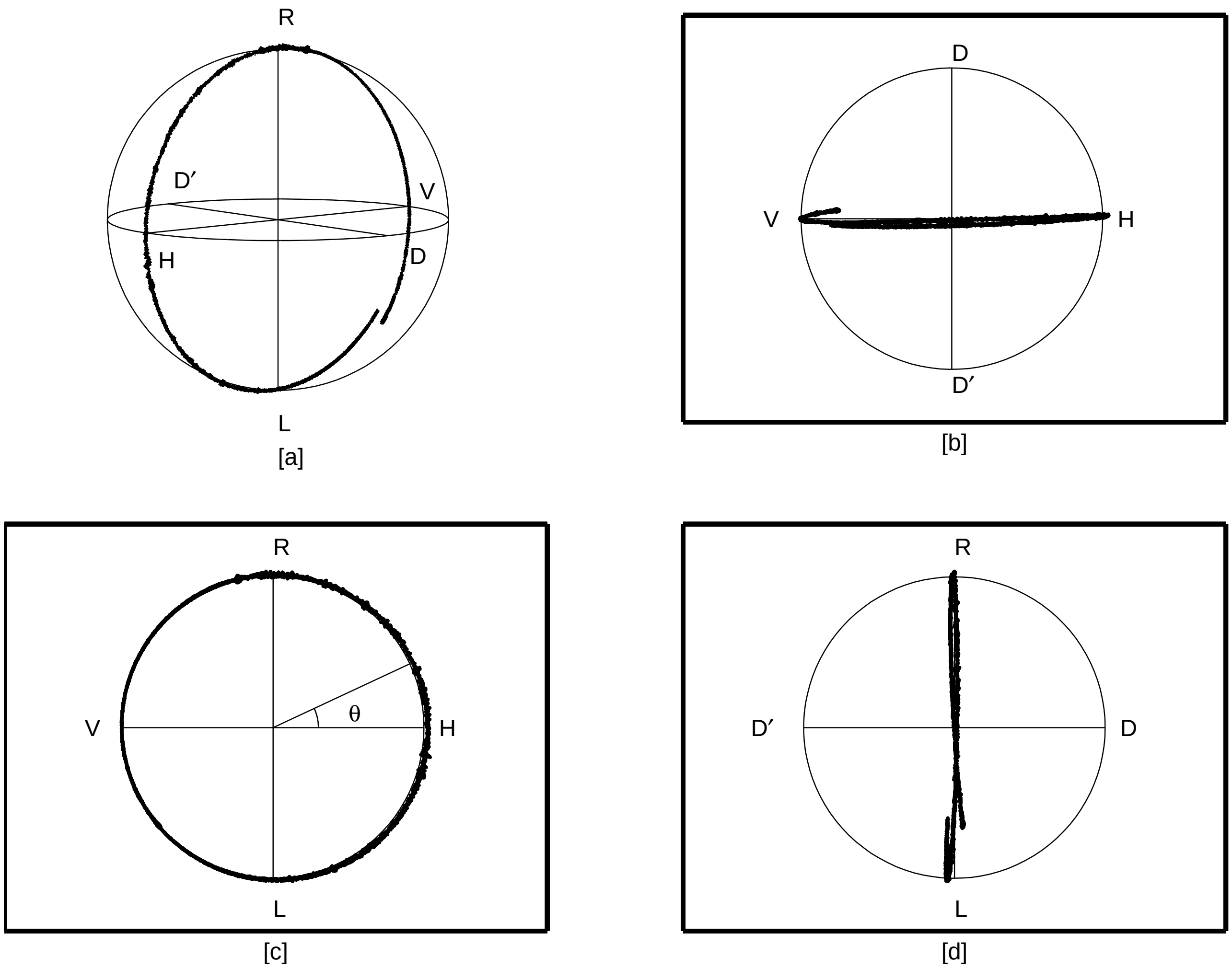

Figure 7. Stokes vector data for the output states of the polarization modulator. Panel [a] shows a 3-D perspective view of the data in the Poincaré sphere. Panels [b], [c] and [d] show the data in the S3, S2 and S1 normal planes, respectively.

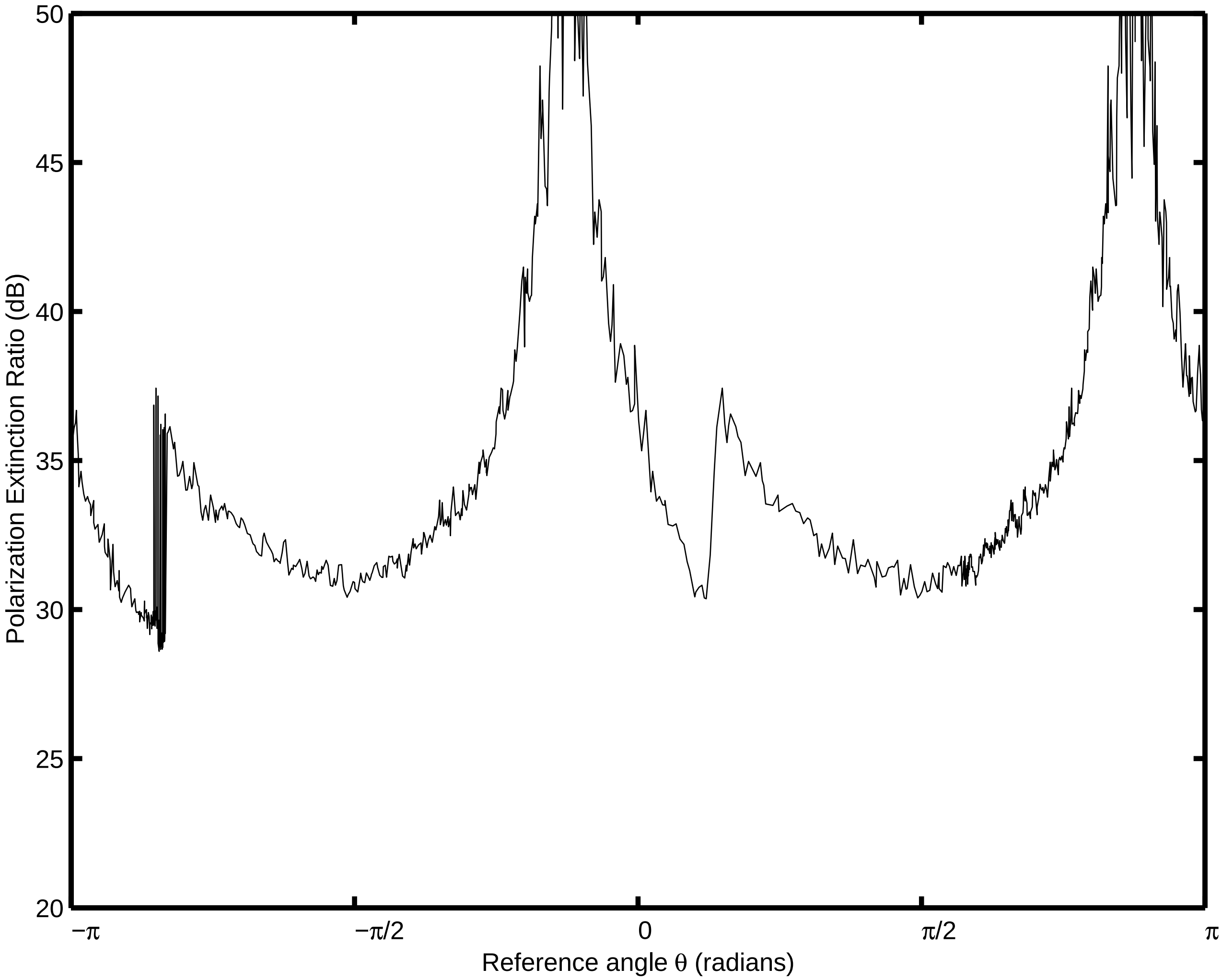

Figure 8. Maximum polarization extinction ratio as a function of the reference angle θ, defined in Figure 7c.

The results presented thus far have shown that the output polarization states of the polarization modulator trace out an HRVL circle in the Poincaré sphere. By adding various optical elements at the output, it is possible to re-orient the HRVL circle to trace out other paths as well. An example of this is shown in Figure 9a, where the output of the polarization modulator has passed through a quarter-wave plate. The result is that the modulator now traces out a great circle through the H, D, V and D' points and therefore the output remains linearly polarized and rotates through 180 degrees. This concept can be generalized to say that by placing the appropriate static polarization controller at the output of the modulator, the great circle which the modulator traces out can be arbitrarily rotated about the origin of the Poincaré sphere. Here, we assume the polarization controller has negligible polarization dependent loss.

As another example, Figure 9b shows the output states of the polarization modulator when passed through a length of single mode fiber. The fact that the orthogonality between states is preserved when the output passes through single mode fiber[8] is key since single mode fiber is a convenient way to deliver a polarization modulated signal to another component in an optical system. By using a polarization controller either before or after the single mode fiber, it is possible to re-orient the final polarization states back to the HRVL circle, or to any other great circle.

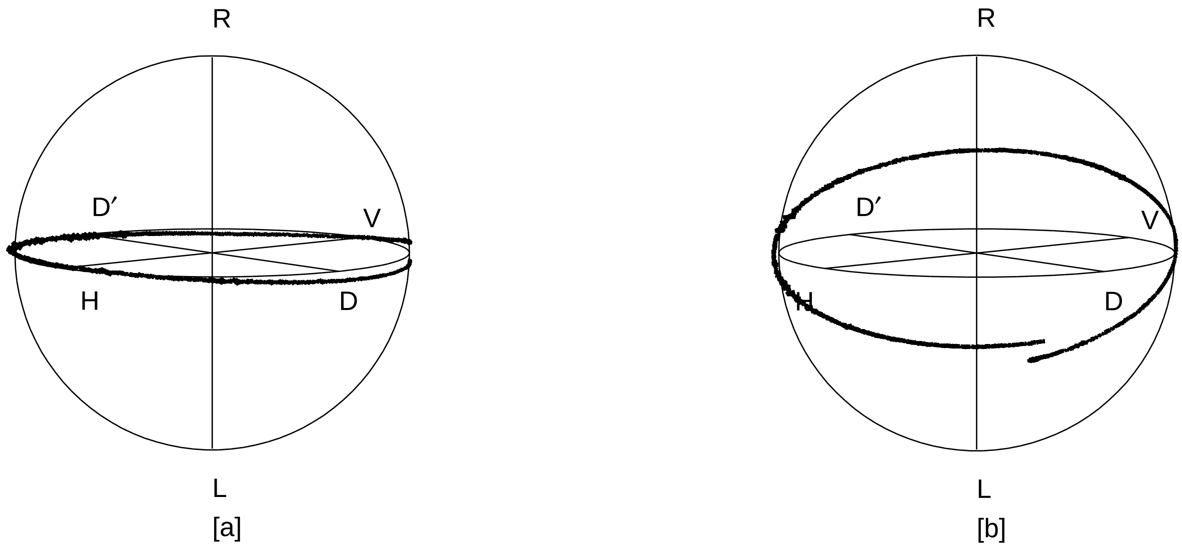

Figure 9. Panel [a] - Stokes vector data for the output states of the polarization modulator with a quarter wave plate at the output. Panel [b] – Example of Stokes vector data for the output states of the polarization modulator with an arbitrary spool of single mode fiber at the output.

4. POLARIZATION CONVERTERS IN ADVANCED MODULATION SCHEMES

Since the introduction of our polarization modulator in September 2003, there has been interest in using polarization modulation to improve the performance of both analog and digital transmission systems. We review work presented this year at the Optical Fiber Conference (OFC 2004) and the Conference on Lasers and Electro-Optics (CLEO 2004) in which our polarization modulators were used. In the first example, it is used to alternate the polarization state of adjacent bits in a system employing return-to-zero differential phase shift keying (RZ-DPSK) to extend the reach to a record setting 2000 km, transmitting over 200 km spans of standard single mode fiber (SSMF) amplified using erbium doped fiber amplifiers (EDFA). In the second example it is used to encode data to reduce inter-channel cross talk in an analog transmission link. We also mention a third application in which the performance of forward pumped Raman amplification can be improved by rapidly changing the state of polarization of the pump. This work reported the enhancements on a transmission system operating at 2.5 Gb/s and did not use our polarization modulator, however as transmission speeds increase to 10 Gb/s and beyond, a polarization modulator with higher bandwidth would be ideal for this application.

4.1 Polarization Alternation

Despite the demonstrated performance advantages of using advanced dispersion minimizing fibers and Raman amplification, focused efforts are being made to maximize the performance of installed fiber links which are predominantly SSMF with EDFA amplification.[2] In the work reported on by Gnauck et al., the polarization state of adjacent pulses in an 42.7 Gb/s RZ-DPSK data stream were made orthogonal using our polarization modulator. The polarization alternation allowed for an increase in the per-channel launch power by 2-3 dBm and resulted in a 10^{-2} reduction in uncorrected bit error rate (BER). The work also demonstrated similar reductions in BER when polarization alternation was used with return-to-zero on-off keying (RZ-OOK).[9]

4.2 Polarization Modulation

Inter-channel crosstalk in analog systems employing wavelength division multiplexing has been reported to significantly degrade performance, particularly in phase sensitive applications such as antenna arrays.[10] Constant amplitude modulation formats such as polarization shift keying have been used to demonstrate significant reduction of inter-channel crosstalk. In polarization shift keying, the information is coded by altering the state of polarization (SOP) of the optical carrier signal. In the work reported by Campillo et al.[11] using our polarization modulator, the crosstalk in a 25 km, 200 GHz spaced analog link was reduced by up to 35 dB at certain wavelengths by using polarization modulation in comparison with conventional amplitude modulation.

4.3 Polarization Sweeping for Raman Amplification

Another application for a high speed polarization modulator was reported by Hu et al.[12] In this work the case was made for reducing the polarization dependent gain (PDG) in a forward pumped Raman amplifier by modulating the SOP of the pump source at a rate faster than the bit rate. To reduce the PDG in a 2.5 Gb/s link amplified using Raman amplifiers, the pump source was modulated at 10 Gb/s. The main goal was to ensure that the modulation rate of the pump source was faster than the bit rate of the signal to ensure that each bit would see more than one polarization state of the pump. In previously reported work on high-speed polarization alternation, a modified lithium niobate phase modulator is typically used. At this time we are only aware of phase modulators with a maximum 3 dB optical bandwidth of 20 GHz. Clearly, as data rates migrate to 10 Gb/s and beyond, faster polarization modulators, such as we present here, will be required to employ this technique.

As of this writing other applications of polarization modulation are being actively explored with another presentation using our modulator expected at the European Conference on Optical Communications ECOC 2004.

5. SUMMARY AND CONCLUSIONS

A novel ultrahigh-speed GaAs based electro-optic polarization modulator was presented. The modulator used a mode converter and a static polarization controller to change the output polarization state in an arbitrary great circle around the Poincaré sphere. The mode converter was constructed using an AlGaAs ridge waveguide and a slow-wave travelling wave electrode structure. The electrodes are designed to match the velocity of the electrical modulating signal to the optical signal in the vicinity of the 3 dB point. This modulator demonstrated a 3 dB bandwidth in excess of 40 GHz. The polarization modulator combines ultrawide bandwidth, extremely low differential group delay, and low drive voltage. These features enable ultrahigh-speed polarization modulation for applications including polarization alternation and polarization modulation for 40 Gb/s applications and beyond.

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