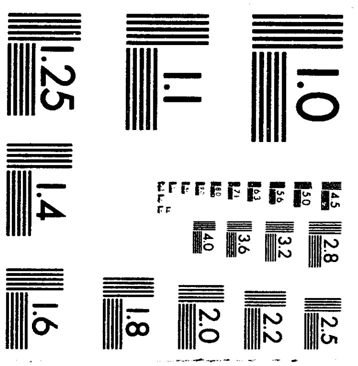
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Abstract

This paper reports on the operation of lithium niobate electro-optic waveguide modulators at temperatures down to 15 °K. Commercial and laboratory fiber pigtailed devices have successfully been cooled without any increases in insertion loss from temperature induced stresses in device packaging. Three x-cut devices exhibited a linear increase in V_π voltage of 8 %±1% when cooled from room temperature to ~20 °K. The broadband frequency response improved at lower temperatures. A velocity-matched experimental modulator has shown increased bandwidth when cooled to liquid nitrogen temperature.

1. Introduction

Lithium niobate waveguide devices have been successfully demonstrated in a broad range of systems. Research centers and commercial firms have characterized lithium niobate devices over both military and commercial temperature ranges . Extending operation of lithium niobate modulators to cryogenic temperatures has been receiving attention for a growing number of applications. Johnston[1] proposes using either lithium niobate or multiple quantum well modulators for transmitting readout signals from a cooled IR focal plane detector. Van Zeghbroeck[2] has proposed using a optical data link for interfacing superconducting circuits with conventional circuitry at room temperature. Tsang[3] reports on temperature effects of lithium niobate devices down to liquid argon(120 °K) for environments found in large particle detectors. Yoshida[4] reports testing of a lithium niobate modulator with superconducting metal electrodes down to cryogenic temperatures for improved frequency response. Finally, Yoshiara[5] has demonstrated a lithium niobate with high temperature superconducting electrodes. These representative papers discuss applications that require detailed testing of low temperature modulator parameters. More complete measurements of the temperature dependence of lithium niobate at cryogenic temperatures are required to allow modulator design for cryogenic applications. We report on further measurements of the low temperature operation of pigtailed lithium niobate waveguide modulators. Two critical concerns investigated are the packaging of pigtailed devices to withstand cryogenic temperatures and the temperature dependence of lithium niobate electro-optical properties.

2. Experimental Procedure

The electro-optic modulators tested at cryogenic temperatures were a combination of modulators fabricated by Lawrence Livermore National Laboratory (LLNL), and commercially available devices from United Technology Photonics(UTP). All of the modulators were fabricated from x-cut lithium niobate with fiber-pigtailed packaging. All of the devices were Mach-Zehnder designs having traveling wave electrodes except one lumped electrode, balanced bridge device architecture. The six devices included in the testing are summarized in Table 1. One of the six tested included an experimental LLNL device (Modulator #1), designed for 50 Ω impedance and velocity matching between the optical and microwave fields.

Table I: Temperature Tested Lithium Niobate Modulators

Manufacturer, electrode type, All are x-cut, y-propagating	Process, wavelength	Cooling induced loss
1) LLNL, TW, 50 Ω	APE 0.8 μm	None
2) UTP, Lumped	APE 1.3 μm	None
3) LLNL, TW	APE 0.8 μm	None
4) UTP, TW	APE 0.8 μm	Loss increased linearly with cooling.
5) LLNL, TW	Ti:in 1.3 μm	Fixed 2.67 dB loss
6) LLNL, TW	APE 1.06 μm	Pigtail crack-complete spillage

Modulator cooling was implemented in two stages using liquid nitrogen and liquid helium. The packaged modulators were placed on a cold finger inside an insulated vessel. The cold finger was gradually cooled by liquid nitrogen in an attempt to gradually lower the temperature of the modulator. Temperature was monitored by a thermocouple gauge attached to the outside of the modulator package. Eventually, the modulator package was partially immersed in liquid nitrogen and maintained to conduct measurements at 77°K. To lower the temperature further, a jet stream of liquid helium was sprayed directly on the modulator package using a helium transfer line. This approach allowed cooling to temperatures as low as 15°K. This cooling technique gave minimal control of the temperature during cooling, but eliminated the need for a dewar with fiber optic modifications.

3. Electro-optic Device Packaging

The packaging techniques developed for LLNL lithium niobate modulators provide low insertion loss, mechanical robustness, and polarization alignment for a temperature range of 0 °F to 120 °F. The most acute packaging concern is the fiber pigtail to lithium niobate wafer interface. The pigtailing process is done in two bonding steps for pigtail mechanical robustness and accurate polarization maintaining fiber(PMF) alignment. First, the stripped fiber is bonded inside a groove in the mounting block of lithium niobate. The orientation of the mounting block matches that of the waveguide device. This was done to match the coefficients of expansion for lithium niobate because they are slightly different in each of the three major axis. Proper alignment of the PMF rod orientation is made with respect to the mounting block surface and epoxy is applied for attachment. Second, the mounting block/fiber unit is then bonded to the lithium niobate device wafer with the correct alignment between the block and device surfaces. UV cured epoxy is used for attachment in both steps. The block gives additional bonding surface at the wafer edge for stronger pigtails over straight fiber to device bonding.

Another concern in packaging is the mounting of the lithium niobate chip to the outer brass package. The lithium niobate ground plane extends to the edges of the long sides of the device, and are used for solder attachment to the brass package. The brass (Naval Bronze Alloy) packaging was chosen to closely match the expansion of the long axis of the lithium niobate (the design numbers were only available from -20° to >120° F).

A final packaging concern for low temperatures is the attachment of the fiber to the brass package at each end of the device providing mechanical strain relief. The fiber between the mounting block and brass package should have some flex induced in the process. This attachment is made using an epoxy which is dried in air at room temperature. The pigtailing process used by LLNL has been successful in achieving commercial temperature range operation. The commercial devices from UTP used in this study are pigtailed in a similar process.

The cooling of LLNL and commercial devices to cryogenic temperatures creates thermal stress at the interface between the different materials, i.e.; lithium niobate and the UV epoxy. The effect of the cooling of six different devices are summarized in Table 1. Three of the six devices operated nominally with no measurable insertion loss increase for one cooling and recovery cycle. The key parameter to prevent damage is good control of the rate of cooling. The experimental set-up used was inadequate providing the sufficient control necessary and damage did occur. The three devices which suffered insertion loss increases with cooling all had in common a >8 °K/minute cooling rate. The high cooling rates caused permanent mechanical shifts in alignment for modulators 5 and 6 from Table 1. Modulator 5 suffered a nearly 3 dB loss in output light when reduced to cryogenic temperature, which remained constant upon recovery to room temperature. Modulator 6 exhibited complete loss of light at a visible crack at the mounting block to wafer interface. Modulator 4 was rapidly cooled causing a 1 dB insertion loss increase. When cooled to 22 °K, modulator 4 exhibited a loss which was linearly dependent on temperature as shown in Figure 1. This effect which was caused by initial excessive cooling rate was notable since the other devices that received damage exhibited a constant insertion loss independent of temperature.

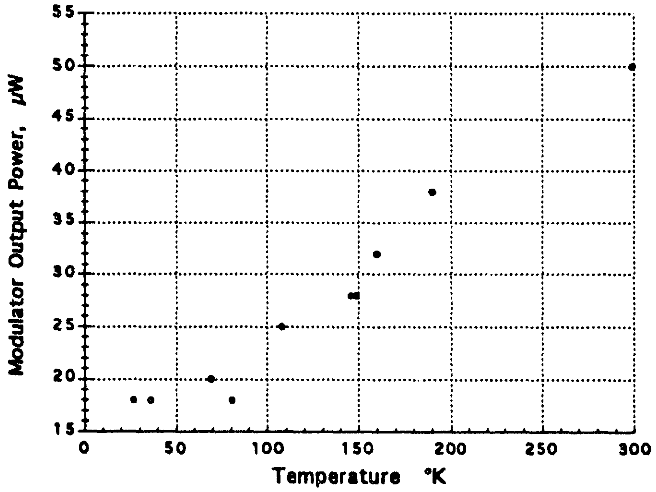

Figure 1: Modulator 4 Temperature Dependent Insertion Loss

In most superconducting applications, the lithium niobate devices will be required to withstand a limited number of temperature cycles during their lifetime. Additional tests are necessary for testing the effect of repeated cycling on the modulator packaging. Even though conventional temperature range packaging for modulators can successfully survive cooling to near liquid helium, reliability and repeated cycling concerns may drive the development of specialized cryogenic temperature packaging. Selection of a customized adhesive, the size of the mounting block, and the incorporation of V-groove technology are some examples of the research areas under consideration to modify modulator packaging methods for cryogenic environments.

4. Temperature Dependence of Modulator Half Wave Voltage

The electro-optical response was characterized as the modulators were lowered to cryogenic temperatures. The system, shown in Figure 2, used to find the electro-optical response utilized a shaped pulse with risetime of ~50 μsec drives the modulator over several fringes. The modulated output signal is optically detected and recorded on a digital oscilloscope. Data acquisition and signal processing are performed with a Macintosh computer running LabView. The electro-optical response measurement records the waveforms and calculates the V_π voltage and extinction. Figure 3 shows the waveforms as collected by the LabView virtual instrument. The V_π value is found by finding the first maximum and first minimum of the optical response or the first full fringe. The corresponding voltage driving the modulator over the fringe is the V_π voltage. The oscilloscope digitizer has 8-bit resolution which contributes to the measurement error of V_π. From Figure 3, it can be seen that the extinction is reduced at high electric field. The extinction is further reduced with decreasing temperature at high voltages. Although further characterization may quantify this effect, it is speculated that the waveguide properties are changing at high fields due to a combination of the temperature dependent index of refraction and birefringence of the lithium niobate.

The algorithm to find V_π required the operating point to be set at the half power point. The bias point was changed by adjustment of the bias supply before each three second data acquisition run. The adjustment was necessary because the phase change with temperature moved the effective bias point along the sinusoidal transfer function of the Mach-Zehnder.

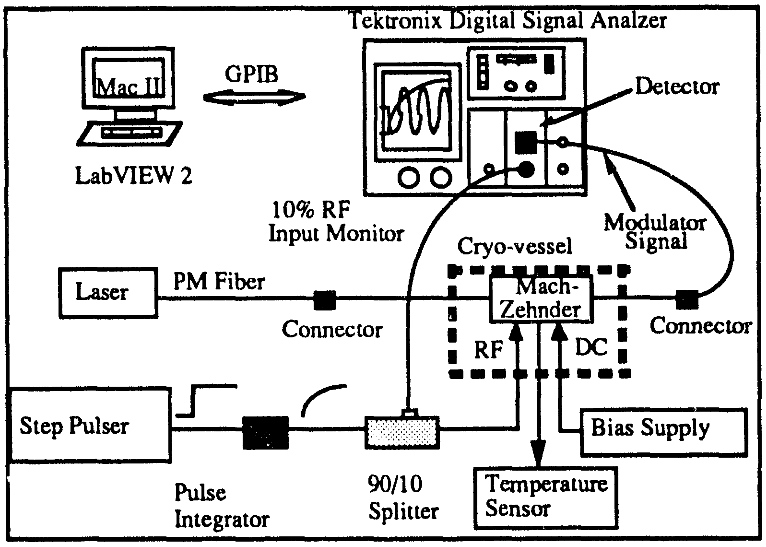

Figure 2: Modulator Electro-Optical Measurement System

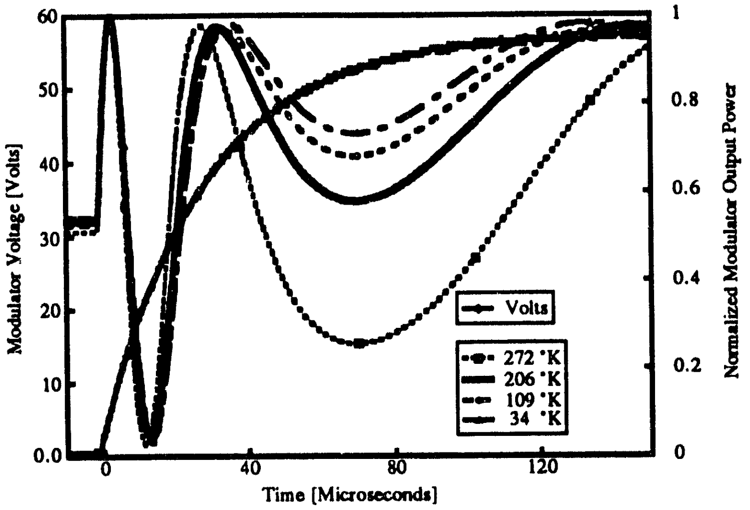

Figure 3: Electro-Optical Response of Modulator 5.

The electro-optical responses of three modulators, devices 2, 4, and 5, were characterized with temperature. The V_π voltage as a function of temperature are plotted in Figure 4 for Modulator 5, and Figure 5 for modulators 2 and 4. Each device tested showed a linear increase in V_π with lower device temperature. A least squares linear curve fit was performed to find the slope. The temperature dependence is found by dividing the slope by the V_π at 300 °K. The results are shown in Table 2.

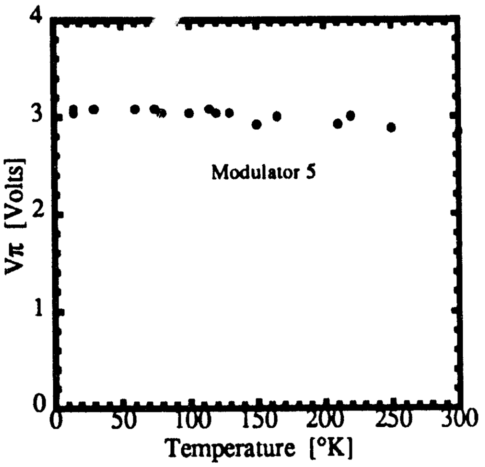

Figure 4: Temperature dependence of half-wave voltage for Ti:in Modulator.

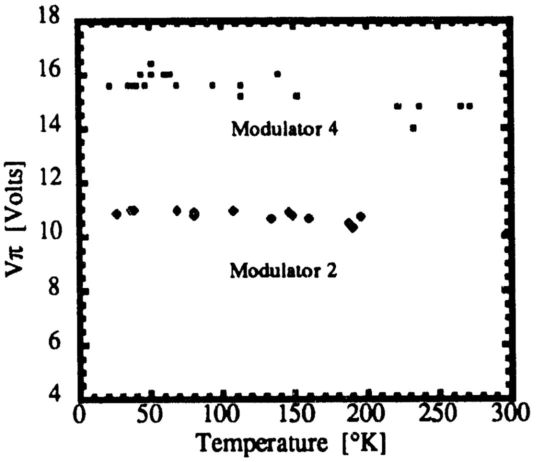

Figure 5: Temperature dependence of half-wave voltage for APE Modulators.

Table II

Modulator#, dV_π/dT Volts/°K	Temp. Dep., $[1/V_\pi(300\ °K)]*dV_\pi/dT$
2) 0.0080 @ 1320 nm Lumped, APE	2.8 x10-4
4) 0.0030 @ 810 nm TW APE	3.0×10^{-4}
5) 0.00505 @ 1320 nm TW Ti:in	3.4×10^{-4}

The Vπ voltage appropriate for TE mode propagation in x-cut, y propagating lithium niobate modulators is expressed in Equation 1. The electro-optical coefficient, r_{33}, and the extraordinary index of refraction, n_e, are the temperature dependent parameters. The other parameters that determine Vπ are electrode gap, G, wavelength, l, electrode length, L, and overlap integral, G. The temperature dependence, Equation 2, for Vπ is made up of the temperature dependencies of r_{33} and n_e.

$$V_\pi(T) = \frac{G\lambda}{L\, n^3_e(T) r_{33}(T)\, \Gamma} \tag{1}$$

$$\frac{1}{V_\pi}\frac{dV_\pi}{dT} = -\frac{1}{r_{33}}\frac{dr_{33}}{dT} - \frac{3}{n_e}\frac{dn_e}{dT} \tag{2}$$

The temperature dependencies of bulk lithium niobate modulators for temperatures above 0 °K have been measured for use of the bulk devices at elevated temperatures to alleviate optical damage problems[6]. For an x-cut Ti:LiNbO3 waveguide device, Fujiwara[7] measured the temperature dependence of V_π over a temperature range from 0 °C to 105 °C. The temperature dependence of V_π was found to be larger in the waveguide device over the bulk device. The authors attributed the enhancement to the Titanium diffusion process. The average electro-optical coefficient temperature dependence [8] is linear and on the order of 5×10^{-4}/°C. For the temperature change from 300 °K to 20 °K, the expected percentage change corresponds to 14%. The effect of index of refraction temperature dependence on V_π is two orders of magnitude less than the effect of the electro-optical coefficient temperature dependence. Yoshida[4] has measured V_π with temperature for a z-cut modulator with superconducting electrodes of Pb-In. The measurement results of temperature dependence of V_π down to 4.2 °K are inconclusive due to errors attributed to mixing of TM and TE modes in the waveguide. These results showed no change in V_π from 300 °K to 4.2 °K above the measurement error bars of 20 %. Tsang[3] has measured V_π with temperature down to 120 °K for two x-cut devices. The linear decrease in V_π with colder temperatures is clearly seen which matches our data. It is interesting to note that Tsang showed a temperature dependence of V_π opposite in sign for a z-cut device.

5. Electro-optic Modulator Frequency Response at Cryogenic Temperatures

Lithium niobate modulator frequency response was measured at cryogenic temperatures for a lumped element device, a traveling wave device, and a velocity matched device. The swept frequency technique[9], along with S_{21} measurements using a network analyzer were used to determine the frequency response at room and cryogenic temperatures. All three types of modulators exhibited improvement in frequency response when cooled. However, the swept data results for modulators 2 and 4 suffered measurement error from the changing bias point as the modulator was cooling. Swept data for modulator 1 was taken at room and stable temperature of 77 °K to avoid pyroelectric effect phase drifts. The frequency dependence is illustrated in swept frequency response shown in Figure 6 for a Modulator 1, a LLNL modulator operating at 0.8 µm. The corresponding S_{21} measurement is shown in Figure 7. This device has been designed to be velocity matched with 50 ohm characteristic impedance. The frequency response at liquid nitrogen temperature is improved over the room temperature response. The improvement in the frequency response at cryogenic temperatures is due to several effects. The largest effect is a decrease in conductor losses for the electrode, with the result being a flattening out of the frequency response over the 0-24 GHz range. Other contributing factors are decreased dielectric losses, and decreased velocity mismatch between the optical and electrical fields. Yoshiara[5] has analyzed electrode effects for non-velocity matched modulators, and shown that conductor losses are the major contributor. Therefore, the use of superconducting electrodes for modulators will significantly improve the performance of high frequency devices. Testing a larger sampling of velocity matched devices could better determine the temperature dependence of the frequency response. Frequency response improvement coupled with a V_π voltage increase at low temperatures allows for design tradeoffs in the modulator electrode design for cryogenic operation.

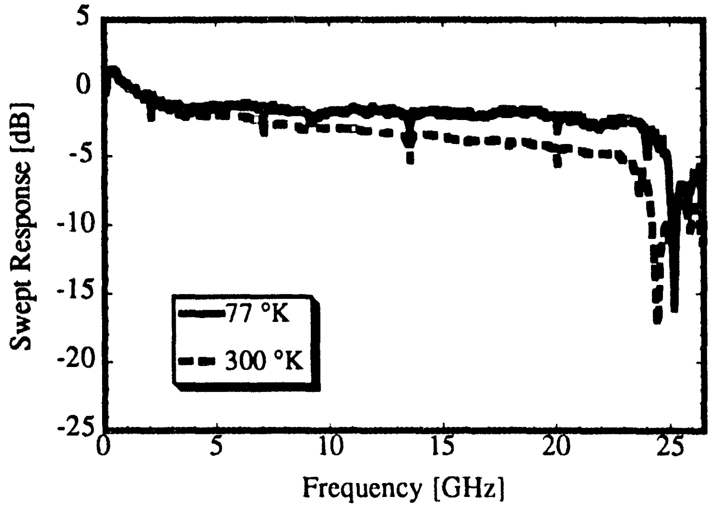

Fig 6: Swept frequency response of velocity matched, 50 Ω modulator at 300 °K and 77 °K.

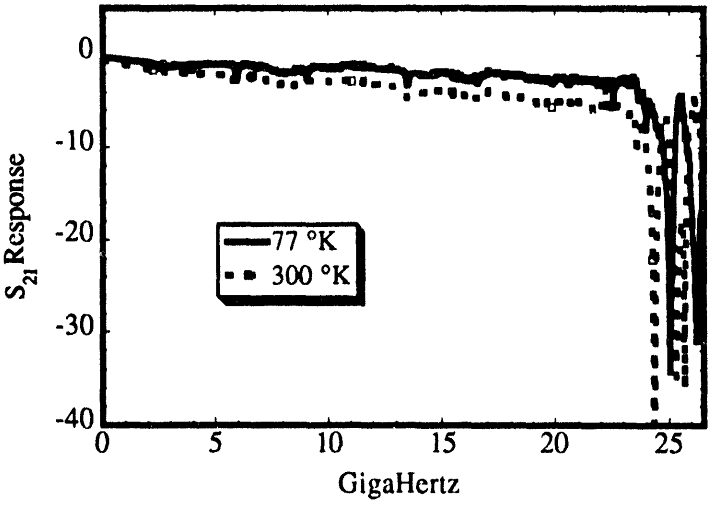

Fig 7: S_{21} response of velocity matched, 50 Ω modulator at 300 °K and 77 °K.

6. Summary

In conclusion, the performance of lithium niobate electro-optic modulators has been characterized at cryogenic temperatures. The results presented demonstrate that with proper consideration of packaging design and testing, the performance of the modulators is marginally degraded, and is actually improved at high frequencies. By reducing microwave losses at higher frequency, the sensitivity-bandwidth product of these devices demonstrates an overall improvement at cryogenic temperatures, thereby making this technology a consideration for optical interfacing to cryogenic circuits and systems.

7. Acknowledgment

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8. References

[1.] Johnston A. R., Liu T.H., "Optical links for cryogenic focal-plane array readout", Johnston, SPIE Proceedings 1946-38)

[2.] Van Zeghbroeck B., "Optical Data communications between Josephson-junction circuits and room-temperature electronics," IEEE Trans. Appl. Sup. 3, 2881(1993)

[3.] Tsang T., Radeka V., "Progress in the Optoelectronic Analog Signal Transfer for High Energy Particle Detectors," Proc. 2nd. Inter. Conf. on Electronics for Future Colliders (May 1992)

[4.] Yoshida K., Ikeda K., Kanda Y., "LiNbO3 Optical Modulator with Superconducting Electrodes", IEICE Trans. Electron., E75-C, 8, pp. 894-899 (Aug. 1992)

[5.] Yoshiara K., et. al., "A study on LiNbO3 Light Modulator Using the Resonant $YBa_2Cu_3O_y$ Superconducting Electrode", IEICE Trans. Electron., E75-C, 1, pp 65-69 Jan 1992.

[6.] Zook J. D., Chen D., Otto G.N., "Temperature Dependence and Model of the Electro-Optic Effect in LiNbO3", Applied Physics Letters, Vol. 15, No. 5, pp. 159-161(Sept 1, 1967)

[7.] Fujiwara T., Kawazoe T., More H., "Temperature Dependence of the Half-Wave Voltage in Ti:LiNbO3 Waveguide Devices at 0.83 μm",

[8.] Lithium niobate: summary of physical properties and crystal structure, Applied Physics A 37, 191-203, 1985

[9.] Uehara, Appl. Opt. 17, No. 1, pp. 68-71, Jan. 1978

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