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Conf-940194--1-
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UCRL-JC-115712 Rev.1
PREPRINT

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This paper was prepared for submittal to the
Fourth Annual ARPA Symposium on Photonics Systems for Antenna Applications
Monterey, California
January 18-21, 1994

January 1994

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Performance Characterization of Photonic Links in Cryogenic Environments for Advanced Signal Processing Applications

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ABSTRACT

Low temperature experiments have been conducted to characterize the performance of high speed photodetectors and LiNbO₃ optical modulators in cryogenic environments down to 4.2°K. Metal-semiconductor-metal (MSM) photodiodes fabricated from GaAs and InGaAs have been characterized. Results demonstrate that both the responsivity and bandwidth depend on temperature. Specific modulator parameters quantified at cryogenic temperatures include bandwidth, V_{π} (half wave voltage), optical loss and package stability. The successful operation of MSM photodiodes and LiNbO₃ modulators at cryogenic temperatures enables a high sensitivity fiber optic approach to superconducting circuit interfaces.

I. INTRODUCTION

Supercomputing, high-speed switching, and signal processing are some examples of applications that are driving the requirements for higher speed electronics. Superconducting circuits can provide a solution to higher speed processing in limited scale. The critical limitation for realizing large scale systems utilizing superconductors is the thermal interface between a cryogenic environment and room temperature. For example, the thermal interface limits the use of superconductors as a central processor in a large computer system. The fast processor located in the dewar must interface with memory at room temperatures since no memory is available which operates at liquid helium temperatures. The processor/memory interface using conventional coaxial cables is limited by attenuation at Gbit/sec data rates. Also the heat load due to the electrical cable interface limits the number of connections and additionally reduces the lifetime of a remote system such as a satellite platform (*Optical links for cryogenic focal-plane array readout, Johnston, SPIE Proceedings 1946-38*). Replacing the electrical lines with optical fibers reduces the thermal load, eliminates electromagnetic interference (EMI), and with the high bandwidth of fiber, allow increased aggregate data capacity through the cryogenic interface.

II. CRYOGENIC OPTOELECTRONIC DEVICE EXPERIMENTS

Operation of semiconductor photodetectors and lithium niobate modulators were evaluated at cryogenic temperatures. For photodetectors, the responsivity, and bandwidth were compared for room and cryogenic temperatures. Lithium niobate modulators were tested for the effects of low temperatures on bandwidth, loss, and V_{π} , or half-wave voltage. This investigation has focused on the use of lithium niobate external modulators over laser diodes for integration with superconducting electronics. External modulators are passive optical devices which dissipate heat only through optical scattering losses in the material and fiber pigtail interface. The external modulator approach allows the laser source to be remotized from the modulator giving flexibility in selecting lasers. The requirement for high sensitivity favors the use of low-noise solid state laser

sources. Examples of these lasers are diode-pumped Nd:YAG lasers at 1.32 μm and a diode-pumped erbium:glass laser at 1.54 μm . The lasers not only give lower RIN noise over semiconductor lasers, but also can provide an order of magnitude increase in optical power available over current DFB lasers. The increased power of solid state lasers can improve link sensitivity in quantum-noise-limited links by increases in the received optical power.

Photodetector Characterization

The performance of GaAs metal-semiconductor-metal (MSM) photodiodes has been characterized at cryogenic temperatures. MSM photodetectors were chosen for their simplicity and ease of fabrication, as well as subsequent integration. Furthermore, MSM performance is comparable to that of PIN photodiodes, which are more complicated for monolithic integration. The cross-section of the MSM photodiode structure is illustrated in Figure 1. The active region of the photodiode is a 1 μm , undoped GaAs layer grown by molecular beam epitaxy, giving high quality. This layer is capped by a 1000Å $\text{Al}_{0.5}\text{Ga}_{0.5}\text{As}$ layer to improve the Schottky barrier, and to reduce the impact of surface defects on the GaAs active region. The fabrication sequence consists of patterning a Schottky barrier metal (Ti/Pt/Au for GaAs) in an interdigitated electrode configuration. The electrode spacing and width typically range from 0.1-5.0 μm . For this work 1 μm electrode spacing designs were used. The length of the electrodes is 50 μm , and the overall active area of the photodetector is 50 μm x 50 μm , thus is well suited for coupling to an optical fiber having a core diameter of 50 μm or less with minimal losses. The photodetectors were mounted on 50 Ω microstrip transmission line coupled using SMA connectors. The photodetector is fiber pigtailed by aligning a 50 μm core multimode fiber over the active region and attaching with UV cured epoxy. The complete package design includes a stress relief fixture in order to minimize the impact of strain on the fiber pigtail as the photodetector is brought down in temperature.

Figure 1: Cross-section of GaAs MSM photodiode structure

Figure 2: GaAs MSM photodetector response at various temperatures.

The GaAs MSM photodiodes were tested using a pulsed laser diode source. The laser diode delivers 1.2 pJ, 20 ps full width half maximum (FWHM), 810 nm optical pulses at a 10 kHz rate. For this experiment, the photodetector is cooled by direct immersion in liquid nitrogen or liquid helium. The resulting transient responses of the MSM photodiode are shown in Figure 2. The bias voltage applied to the MSM is 1 V. The transient response tracks the optical signal to first order, and is limited by the mounting fixture to a rise time of ~25 ps and a pulse width of ~35 ps. At room temperature the falling edge of the transient response exhibits a tail, which is likely due to the associated time for complete sweepout of the charge by the electric field between the electrodes. At 77°K, the photodetector response exhibits dramatic changes. The amplitude of the transient

response increases by a factor of three. Furthermore, the tail on the falling edge is eliminated, with only a small reflection remaining, which is due to the package and bondwires. These effects are intuitive since the carrier mobility, hence drift velocity, increases as temperature is decreased due to reduced phonon scattering. This is observed in the photodetector response since the photocurrent and carrier transit time are directly related to the carrier velocity. At 4.2°K, the amplitude of the photodiode response is roughly 10% less than at room temperature. The falling edge does not exhibit a tail, but the reflections remain. Interpretation of this result is difficult since competing processes exist which are not precisely quantified. The relevant physical processes include increased impurity scattering, which will dominate the phonon scattering at this temperature, thus some reduction in mobility is expected. The manner in which this effect impacts each type of free charge carrier will determine the effect on the photodetector transient response. Another physical effect which cannot be overlooked is the increase of the semiconductor bandgap at low temperatures. This is particularly important for this case since the laser diode optical wavelength is near the band edge. This results in an increase of the absorption depth, therefore charge carriers are photogenerated further from the surface where the electric field strength is much less. The drift velocity of these carriers will be less than at high electric fields, and the contribution to photocurrent will be reduced.

Electro-Optic Modulator Testing

The electro-optic (EO) modulators tested at low temperatures were a combination of modulators fabricated by Lawrence Livermore National Laboratory (LLNL), and commercially available devices from United Technology Photonics (UTP). All the modulators were made from x-cut lithium niobate and had fiber-pigtailed packaging. All the devices were Mach-Zehnders with traveling wave electrodes except one lumped electrode, balanced bridge device design. Also, an experimental LLNL device designed for 50Ω impedance and velocity matching between the optical and microwave fields was tested at cryogenic temperature.

The modulator cooling process was implemented in two stages using liquid nitrogen and liquid helium. The packaged modulators were placed on a cold finger inside a two-stage, insulated refrigeration system. The cold finger was gradually cooled by liquid nitrogen to slowly 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, where it was 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 10°K. This cooling technique gave minimal control of the temperature during cooling, but eliminated the need for a dewar with fiber optic modifications. The next phase of testing will use a shielded helium dewar to contain the superconducting circuits and modulators.

Modulator Packaging. The fiber pigtail to lithium niobate interface is the critical packaging concern. Thermal stresses at the interface are induced as the dissimilar materials contract with lower temperature. We have encountered insertion loss increases for cooling rates which exceeded 20 °K/minute. One device suffered a physical shift and permanent misalignment of the fiber to niobate interface. Another device shifted and caused a 3 dB loss while cooling at a rate of 26 °K/minute. However, LLNL and commercial devices cooled at lower rates resulted in no temperature induced insertion loss during cooling and cycling back to room temperature. The use of conventional robust modulator packaging and moderate cooling rates were shown to be operate as low as 10°K. Additional tests are required for testing the effect of repeated cycling on the modulator packaging.

Temperature Dependence of Modulator V_{π} Voltage. The experimentally measured temperature dependence of V_{π} for three different EO modulators is shown in Figure 3. An $8\% \pm 1\%$ increase in V_{π} for cooling from 300°K to 10°K was found for the three devices. The specific devices tested

consisted of an LLNL 1.3 μm traveling wave Mach-Zehnder, a UTP 0.8 μm traveling wave MZ, and a UTP 1.3 μm lumped balanced bridge modulator (MZ with a directional coupler for complementary outputs). All three devices exhibited the same linear rate of increase in V_π within experimental error. Lithium niobate modulators can be placed alongside low-temperature superconducting circuits with a <10% degradation in link sensitivity.

Temperature Dependence of Modulator Frequency Response. 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 was used to determine the frequency response (Uehara, Appl. Opt. 17, No. 1, pp. 68-71, Jan. 1978). All three types of modulators tested showed no degradation in frequency response when cooled. A representative swept frequency response is shown in Figure 4 for a LLNL traveling wave Mach Zehnder operating at 0.8 μm . 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. Testing a larger sampling of velocity matched devices is underway to determine the temperature dependence of the frequency response. Frequency response improvement coupled with a V_π voltage increase at low temperatures allows design tradeoffs in the modulator electrode design for cryogenic operation.

III. CONCLUSION

The performance of high speed photodetectors and electro-optic modulators has been characterized at cryogenic temperatures to determine the viability of interfacing superconducting electronics with fiber optic transmitters and receivers. The electro-optical characteristics of GaAs photodetectors and LiNbO₃ EO modulators at cryogenic temperatures are not significantly changed from room temperature operation. Furthermore, the packaging of optoelectronic devices which include optical fiber pigtails has proven to be robust enough for cryogenic temperature transitions, given that appropriate care is taken in introducing the packaged components to the cryogenic environment. The necessary electro-optical devices for a fiber optic transmission system have been shown to operate nominally at the cryogenic temperatures necessary for placement with low temperature superconductor circuitry.

Figure 3: Temperature dependence of V_π for various LiNbO₃ EO modulators.

Figure 4: Temperature dependence of LLNL EO modulator frequency response.

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This work was supported by the U.S. Department of Energy by the Lawrence Livermore National Laboratory under Contract W-7405-ENG-48.

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