LARGE BANDWIDTH OPTICAL MODULATORS UTILIZING MILLIMETER WAVELENGTH DRIVERS*

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ABSTRACT

This paper describes the research and development effort under way at Hughes Research Laboratories (HRL) to design, fabricate, and test infrared traveling-wave modulators that can be excited by millimeter-wavelength drivers. The modulators are designed for eventual use in high-data-rate communication systems and for laser wavelength shifting in isotope separation experiments. These programs have demonstrated that millimeter-wavelength excited infrared modulators have the potential to advance the state of the art for optical modulation bandwidth by a factor of three and reduce driver power by at least an order of magnitude.

Introduction

As the driver frequency of a conventional optical modulator is increased above a few hundred megahertz, inefficiency caused by the optical transit time through the device can be circumvented by inserting the electro-optic material into a microwave transmission line operating in a mode in which the phase velocity of the optical wave in the dielectric is synchronous with the phase velocity of the propagating microwave field. This velocity-matched condition is shown as the region Δf in Figure 1, where the optical velocity (c/η_o) matches the velocity of a millimeter-wavelength signal in a dielectric loaded waveguide. Because of the velocity-matching conditions, for a constant driver power, the interaction of the two waves is accumulative along the length of the electro-optic material and modulation increases directly with the length of the transmission line.

Our infrared-millimeter wavelength interaction studies at HRL began with an experimental loss tangent study of 20 electro-optic materials resonated at 60 GHz. These measurements found CdS, ZnO, GaAs, and CdTe to have an order of magnitude less loss than the other materials studied.[1] The next phase of this study for the Air Force Avionics Laboratory (AFAL) was an experimental program to determine the effects of dielectric loading on the bandwidth, velocity dispersion characteristics, and interaction impedance of several of the more promising traveling-wave interaction structures. A trade-off comparison was then made to optimize material, optical-wavelength, and millimeter-wavelength structure parameters with the goal of minimizing driver power so that the unit would be compatible with 4 Gbit drivers developed in a parallel AFAL program.[2] We found that the CdTe loaded waveguides, vane lines, and coupled-cavity structures offer the most promise for modulator use when taking advantage of velocity-matched interactions over long interaction distances (>1 cm).

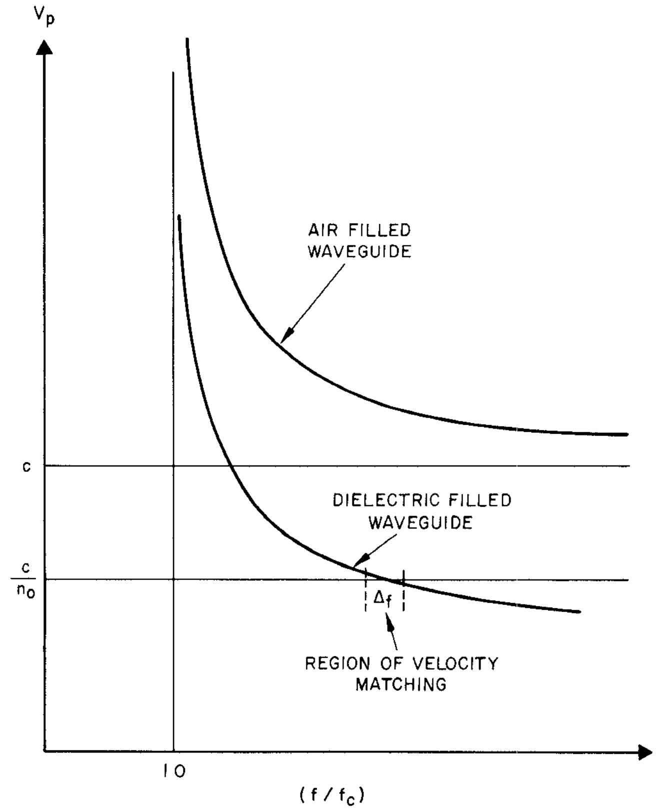

Figure 1. Normalized plot of waveguide velocity V_p as a function of frequency. The millimeter velocity and optical velocity c/η_o are matched in the region Δf.

High-Data-Rate Modulator Experiments

Our infrared modulation experiments for AFAL began by fabricating the waveguide traveling-wave resonator structure shown in Figure 2. In this device, a side-mounted 60-GHz waveguide is matched into a CdTe dielectric waveguide resonator (Figure 2 between B and C). The millimeter energy is confined in the 45-mm-long crystal by channels (A and D) that allow the laser beam to pass but are waveguides beyond cutoff at 60 GHz acting as rf short circuits. Resonator Q's between 300 and 800 are obtained with this configuration giving driver power reductions of at least an order of

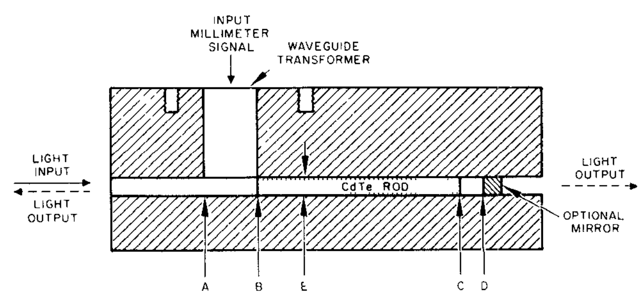

Figure 2. Cross-sectional view of dielectric waveguide structure.

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magnitude over nonresonant devices. The transverse dimensions (E) of the various CdTe crystals used were adjusted to velocity match the laser- and millimeter-wavelength signals. To date, our work has centered around 35 GHz and 55 GHz.

Figure 3 is a drawing of a typical experiment. The optical modulation can be monitored by using the output of a 1000-Hz amplifier or by observing the optical sidebands with an optical spectrum analyzer. The bandwidth of the Δf region shown in Figure 1 was measured by comparing the depth of optical modulation as the driver and structure were tuned between 50 and 60 GHz. The 3-dB bandwidth measurement, shown in Figure 4, was limited by the tuning range of the driver tube; however, it is in excess of 8 GHz. This bandwidth is a factor of three advance in the state of the art for optical modulator bandwidth.

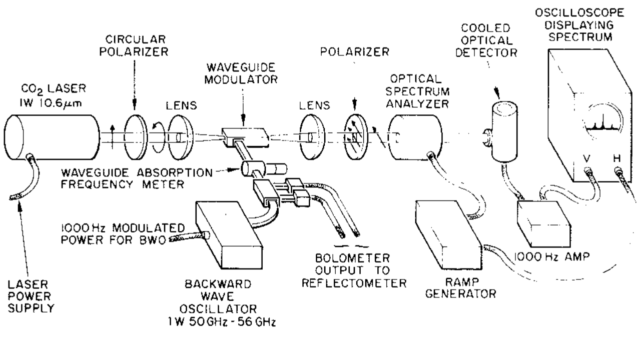

Figure 3. Experiment demonstrating millimeter wavelength modulated laser beam.

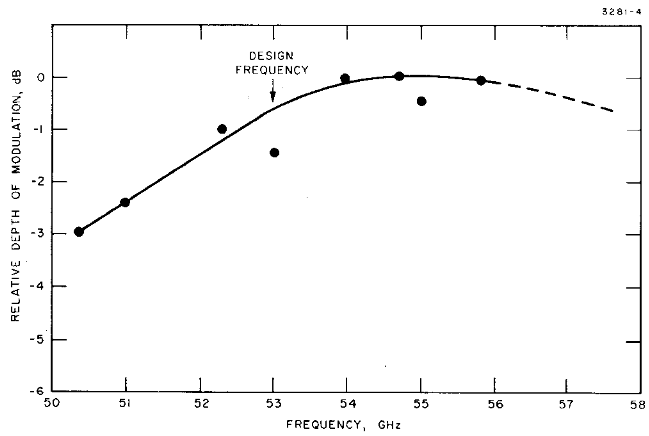

Figure 4. Waveguide modulator response at 3.39 μm.

In another experiment, we measured the depth of modulation for a single optical pass through a 45-mm-long CdTe crystal. With 1 W of millimeter driver power, 0.1% AM modulation was produced at 10.6 μm and 10% AM modulation was produced at 3.39 μm. By placing a mirror on the end of the CdTe rod, we were able to place the device inside the optical cavity of a 10.6-μm CO_2 laser. We anticipate at least a factor of 10 improvement in modulation efficiency using the device in this manner as a coupling modulator. An application of the intracavity device would be the generation of a tunable laser local oscillator for doppler tracking in fast-moving 10.6 μm systems.

Because of the low impedance of a waveguide transmission line, the peak electric field that can be produced is lower than that of many bandpass circuits. Such structures can increase the impedance by factors of 10 to 100 and allow the possibility of velocity matching over large bandwidths, as shown by the dispersion diagrams in Figure 5. For example, the structure shown in Figure 6 consists of seven coupled-cavity resonators of the type used in traveling-wave tubes. This optical modulator, when loaded with CdTe, can provide 10% bandwidths, as shown in Figure 7. Unfortunately, the complexity of these structures makes them difficult to fabricate with little control for fine tuning the velocity once the expensive circuits are fabricated.

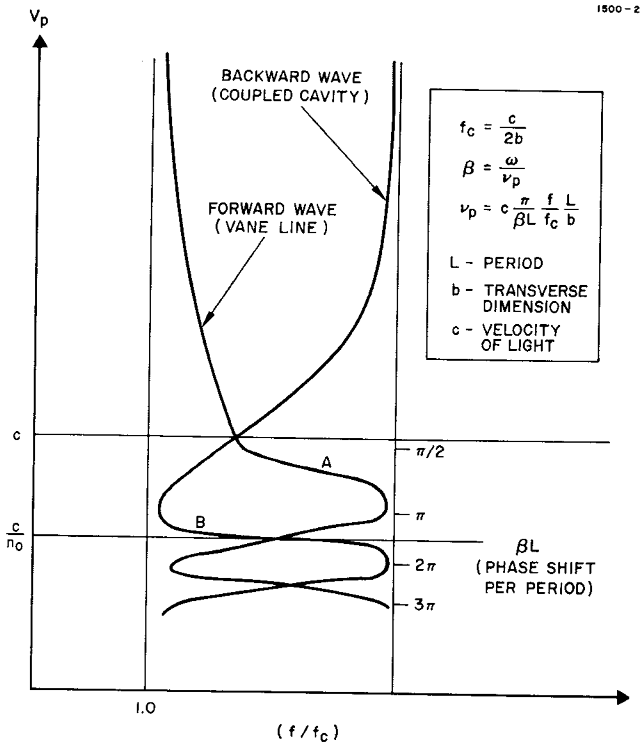

Figure 5. Typical velocity dispersion curves for the coupled cavity and vane line structure normalized to the cutoff frequency f_c.

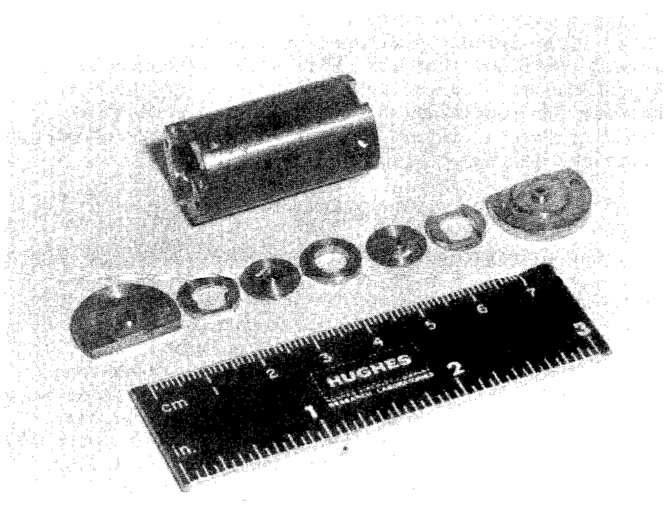

Figure 6. Exploded view of a 3-resonator coupled cavity modulator for use at 35 GHz.

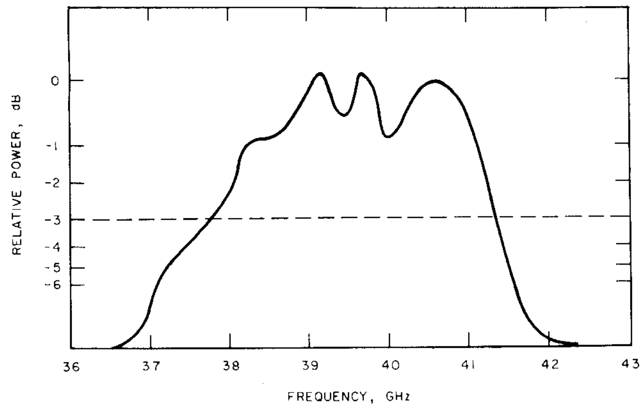

Figure 7. Typical coupled cavity passband response curve for seven-cavity structure loaded with CdTe.

We are now studying the vaneline structure shown in Figure 8. This structure, which is used in our millimeter-wave backward wave oscillators, has a 10-GHz bandwidth at 60 GHz when loaded with CdTe. The vaneline is relatively inexpensive to fabricate and the circuit parameters are easily adjusted.

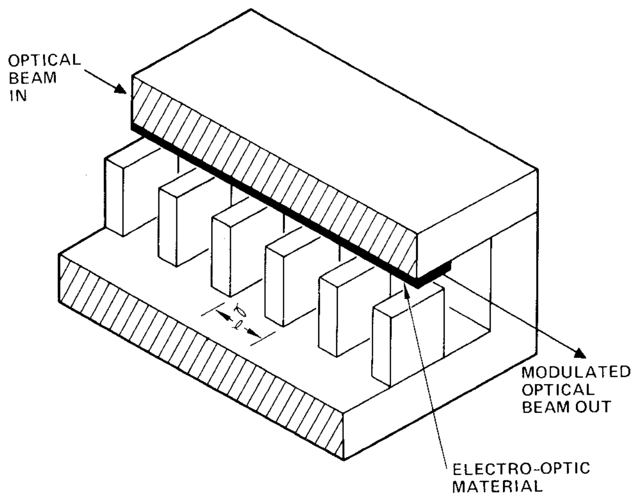

Figure 8. Vaneline traveling-wave guided-wave modulator.

Laser Wavelength Shifting Studies

The traveling-wave dielectric waveguide resonator is also a promising device for shifting laser wavelengths for isotope separation experiments, and we have tested a scaled-up version of the AFAL waveguide resonator at 35 GHz for the Los Alamos Scientific Laboratories (LASL). This device has produced 30% AM at 10.6 μm using 4-kW driver pulses from a 35-GHz magnetron, a factor of 10 improvement over nonresonant structures.

We are also studying a unique single optical sideband suppressed optical carrier (SOSSOC) infrared modulator configuration for LASL that might be used to frequency shift a 16-μm laser to precisely coincide with molecular resonances in UF_6 molecules. To accomplish this translation between 30 and 40 GHz, we are adapting 100-MHz transit time limited SOSSOC techniques developed by Buhrer et al.[3] to millimeter wavelengths. This device, now under development at HRL (Figures 9 and 10), interacts circularly polarized infrared and millimeter wavelength signals, with the up or down frequency shifting from laser line center being determined by the relative sense of polarization between the two signals. The goals of the programs are to use a magnetron-to-frequency shift at least 10% of the energy from a high-power pulsed 16-μm laser.

Conclusions

The use of multiple phase-modulated millimeter-wavelength subcarriers, frequency multiplexed in the passband of a traveling wave optical modulator, may eventually allow data rates in excess of 8×10^9 bits per sec to be efficiently placed on an optical carrier. The waveguide resonator and other periodic structures under development at HRL may eventually enable the great bandwidths available at optical wavelengths to be used in the same manner that data channels are now multiplexed on microwave links.

The SOSSOC infrared modulator is a promising technique for laser isotope separation and molecular spectroscopy. The device will enable high-power, tunable optical signals to be derived from the vast number of fixed laser lines located throughout the infrared and submillimeter spectrum.

References

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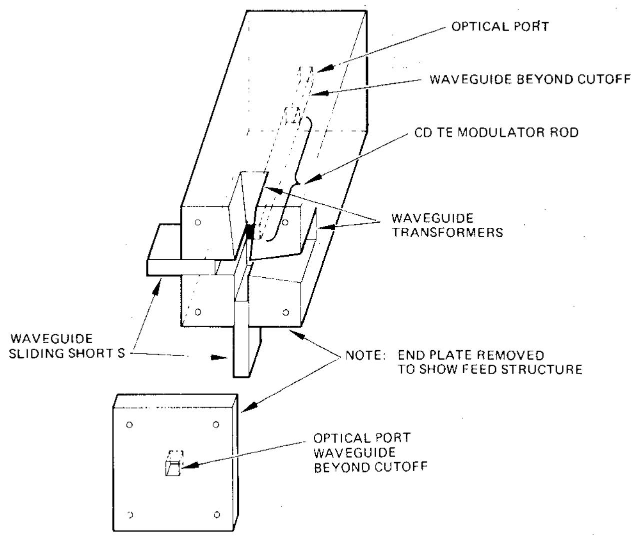

Figure 9. SOSSOC waveguide resonator modulator

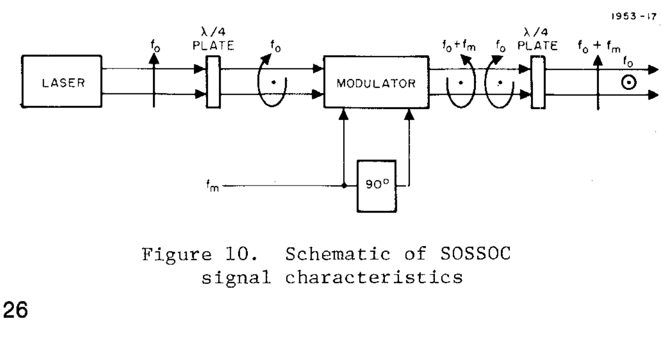

Figure 10. Schematic of SOSSOC signal characteristics