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Antenna-Coupled Millimeter-Wave Electro-Optic Modulators for 20 to 100 GHz

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ABSTRACT

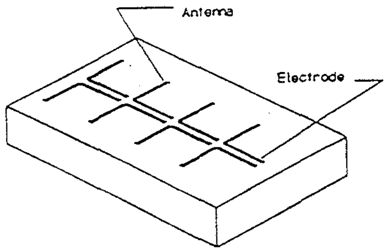
Coupling the signal to the electrodes of an integrated electro-optical modulator with an array of antennas is used to velocity-match the modulation and optical waves, greatly extending the length-to-modulation frequency product of the modulator. In addition, antenna coupling eliminates the parasitic elements associated with coax connectors, matching transformers and bond wires. This paper summarizes the results obtained to date with this technique at 20 to 100 GHz, with phase modulators, Mach-Zehnder modulators, and delta-beta directional coupler modulators.

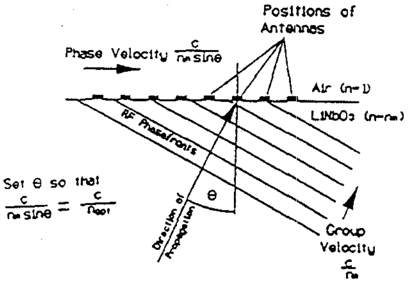
BACKGROUND

A key problem in extending integrated lithium niobate electro-optic modulators to mm-waves is the velocity mismatch between the optical wave velocity (c/2.2) and the effective velocity on the traveling-wave modulating electrodes (about c/3.8 in lithium niobate.) This mismatch limits the length of the modulator and hence its sensitivity, and various schemes have been tried to overcome it. Using a thick SiO_2 buffer layer and thick electrodes, the effective transmission line velocity can be made to approach c/2.2, but at a sacrifice of sensitivity, since a smaller fraction of the modulating electric field now exists in the optical waveguide [1]. Alternatively, the line can be broken into short segments, with each segment driven at a phase corresponding to a phase velocity of c/2.2 from segment to segment. The periodic phase-reversal modulator [2], and the space-harmonic modulator [3] are examples of this latter technique.

Antenna-coupled modulators also segment the transmission line. Each segment is driven by an antenna integrated on the surface of the modulator as shown in Fig. 1, and the resulting array illuminated by a plane wave incident at an angle to provide a phase velocity of c/2.2 from antenna to antenna. An advantage of this technique over that of refs. [2, 3] is that the resulting bandwidth is that of a single antenna/line-segment, and does not narrow with increasing number of segments. Another advantage is that the parasitic-prone connections from coax to modulator transmission line usually employed (even more difficult to realize in the mm-wave range) are replaced by quasi-optical coupling; the resulting structure is as simple as a lithium niobate chip illuminated by radiation from a r-f

Fig. 1





waveguide. In fact, the modulator chip may be thought of as a high-gain, directive phased-array antenna, with beamwidth given by the modulator length.

EARLIER WORK

We have previously reported the performance of antenna-coupled electro-optic modulators at 10, 60 and 94 GHz using titanium-diffused optical waveguides in lithium niobate [4,5]. The 10 GHz version used five antenna/transmission line segments totalling 25 mm in length, and was a simple phase modulator. The antennas were two-half-waves-in-phase and the transmission lines a half wave long at 11 GHz. The line segments are open-circuited at the far end, producing a standing-wave on the segment; however, the optical radiation interacts primarily with the forward-traveling wave, as discussed in ref. 6. The excitation was coupled in from the substrate side from open-ended WR-90 waveguide via a wedge of $\varepsilon = 30$ artificial dielectric and l/4 matching layers, as shown in Fig. 2.

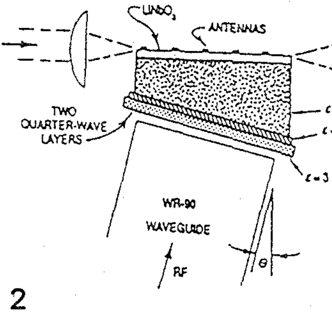


Fig. 2

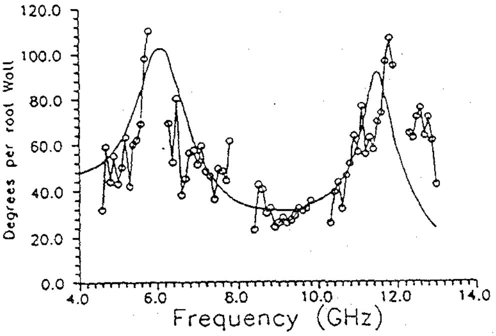
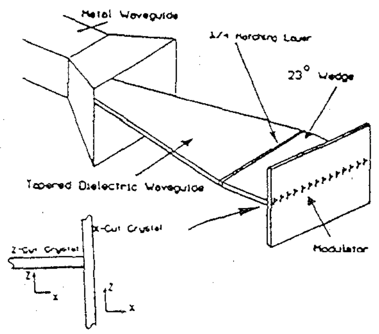


Fig.3

The phase modulated light (633 nm) was detected with a scanning Fabry-Perot interferometer, and the amplitude of the modulation sidebands was used to deduce the depth of modulation (Fig. 3). The second peak at 6 GHz is the resonance where the antennas are simple half-wave dipoles and the transmission lines are a quarter-wave long. Both the 6 GHz resonance and the 11 GHz resonance are broad enough so that there is significant modulation over the region between them. Increasing the length of the modulator will not change this curve. The solid line in Fig. 3 is the result of a simple transmission-line model for the antenna impedance [6]

The same antenna/transmission line element was scaled down by one sixth in size, and 25 of them were used along 18 mm of optical waveguide to make a phase modulator for 60 GHz, as shown in Fig. 4. The feed system had to be changed, since the modulator length no longer matched the width of standard 60 GHz waveguide, WR-15. A 1 mm thick polypropylene slab waveguide was tapered from the WR-15 width, 3.8 mm, to the 18 mm necessary to illuminate

Fig.4



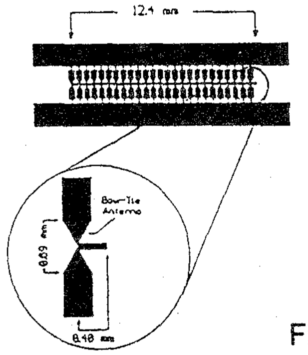


Fig.5

the antenna array. A thin quarter-wave slab of stycast $\varepsilon=9$ was interposed between the plastic slab and the wedge-shaped lithium niobate slab waveguide, $\varepsilon=28$. The 1 mm thickness of the lithium niobate wedge matches the approximately 1 mm length of the 60 GHz dipoles. The best performance was about $80°/\sqrt{W}$ (633 nm)

A Mach-Zehnder amplitude modulator were also designed and fabricated for 94 GHz use with 1.3 micron lasers. This modulator utilized broadband bow-tie dipole elements, and required d-c bias connections to each segment, as shown in Fig. 5, to bias the Mach-Zehnder to the correct operating point. The 94 GHz modulator used 25 segments to cover a 12 mm modulator arm length. (The interaction length is shorter for the M-Z because the Y-arms take up some of the real estate.) Only one arm of the M-Z was modulated. The 94 GHz modulator performance yielded a value of m^2/Watt of 0.072 (@ 1.3 micron), which agrees well with the value expected by scaling the phase modulator results at 60 GHz in interaction length and laser wavelength [6]. The true operating bandwidth of the modulator was not determined due to lack of a widely tunable mm-wave source, but appeared to be flat ± 2dB over the 91 to 98 GHz range of our klystron. The antenna-limited bandwidth should be much larger [7].

RECENT RESULTS AND WORK IN PROGRESS

Potential applications for mm-wave fiber optic links require high dynamic range performance, better than that possible with simple modulators. A separate study [8] suggests that a $\Delta\beta$ directional coupler modulator (DCM) would be easier to linearize for high dynamic range applications than a M-Z modulator. Thus a mm-wave DCM was designed and fabricated using the wave-coupling concept. The electrodes overlay a two-waveguide directional coupler in a z-cut $LiNbO_3$ substrate. Eighteen resonant dipole/transmission line segments similar to Figs. 1 and 3 were used over a 10 mm length of the coupler, sacrificing bandwidth to enhance sensitivity. No bias connection were made to the modulator region itself; rather, d-c biased regions preceding and following the r-f section are used to adjust the overall DCM transfer curve to the correct operating point and potentially allow some linearization. This feature initially caused difficulties, since DCM's produce both amplitude and phase modulation simultaneously, and lacking a 94 GHz optical detector, sideband amplitude alone is insufficient to determine the correct operating condition. To complicate the issue further, we found that the optical directional coupler had a built-in $\Delta\beta$ of size comparable to the electro-optical $\Delta\beta$. Once the theory was modified to include this feature, the proper bias points were predicted and the modulator operated successfully, with m^2/Watt = 0.2 (@1.3 micron) as determined from the sideband amplitudes. This is more than 3 times better than the previous 94 GHz M-Z. We are currently fabricating additional samples of this design and working to improve the tapered slab waveguide feed system.

A rather different wave-coupled modulator has also been conceived and is currently being fabricated. This design, shown in Fig. 6, uses slot-vee broad band antennas coupled to transmission line segments. The entire surface of the modulator is covered with metal, and the vee antenna elements are wedge-shaped openings in the metal coating. These antennas are directional along the plane of the modulator chip, rather than radiating downward into the substrate. In this modulator, the radiation is coupled into the antennas by using the chip itself as a dielectric waveguide, (actually dielectric image guide, because of the metal coating.) Phase velocity matching is obtained by canting the optical waveguides to the direction of the mm-wave excitation. Another new feature of this configuration is that the transmission line segments are effectively "terminated" by putting a second antenna at the far end, radiating the excitation back into the image guide. This modulator should have an antenna-limited bandwidth of more than an octave. A version of this modulator for 20 GHz is currently being fabricated

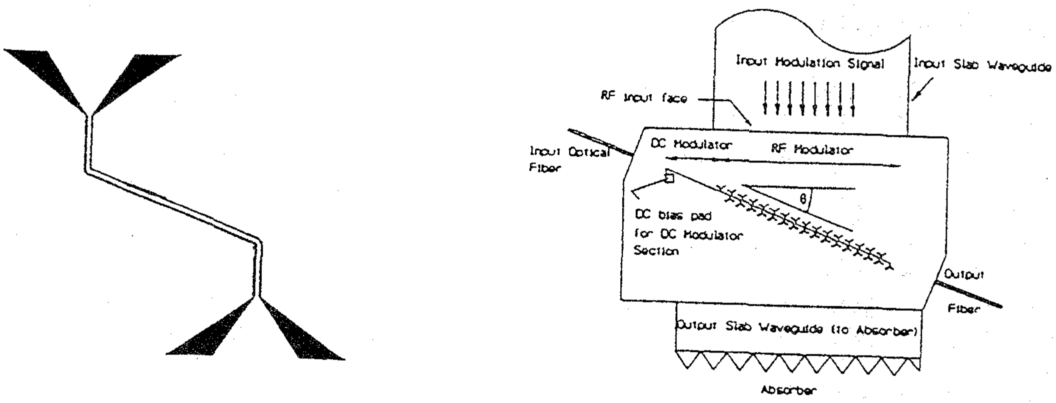


Fig. 6

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