Demonstration of 110 GHz electro-optic polymer modulators

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Electro-optic modulation up to 113 GHz has been demonstrated using traveling wave polymer modulators. The modulation signal was directly detected at 1.3 μm using a laser heterodyne system with an external-cavity tunable semiconductor laser. The device optical response variation, as a function of frequency over the whole W band, was within 3 dB. A well-matched coplanar probe was used to launch W band millimeter wave driving power into the microstrip line electrode on the device. Based upon these measurements, high speed electrodes with integrated millimeter wave transitions had been fabricated and tested. © *1997 American Institute of Physics.* [S0003-6951(97)03125-2]

Polymer materials have become increasingly important for integrated optics[1] because of their low dispersion and fast electronic response. Decades of research[2–5] on nonlinear electro-optic polymer materials have made it possible to make high frequency photonic switching and modulating devices.[6–10] Recently our group demonstrated frequency response of an electro-optic polymer modulator up to 60 GHz,[10] and measured its frequency-length product to be well above 100 GHz cm.[11] However, in extending these measurements beyond 60 GHz, the millimeter wave circuits become more complex, and electro-optical phase modulation characterization becomes more demanding. In this letter, we report our latest high frequency measurement results over the whole W band (75–110 GHz) and up to 113 GHz.

The device being tested was a traveling wave polymer phase modulator.[12] The optical wave propagates along a vertically stacked optical ridge waveguide, which consists of a poled PUR-DR19 active core sandwiched between lower and upper claddings made of Epoxylite 9653. The driving millimeter wave electric field propagates along the microstrip line on top of the upper cladding in the same direction as the optical wave. Because of polymer's low index of refraction and low dispersion, we were able to use a straightforward traveling wave design to achieve velocity matching between the millimeter and optical waves. For high frequency operation, the main problems are to effectively couple the millimeter wave driving power into the microstrip line on the device and to reduce the microstrip line Ohmic loss. In this demonstration we used high frequency coplanar probes to drive the microstrip line electrode on the device in well-matched configurations at 61 GHz, and from 74 to 113 GHz.

A dc probe tip was used to precisely open small holes on the thin polymer dielectric layer at both sides of the microstrip line and to expose the ground contact regions. The distance between the coplanar probe tips is 100 μm, and the dielectric layer is only 10 μm thick so the three probe tips made an effective contact with a spring loaded contact mechanism. We also measured the contact resistance before doing the measurement. To reduce the microstrip line Ohmic loss, we improved our fabrication process by changing our gold-plating recipe. A pulse/reverse current through a non-cyanide-based solution yielded a thicker line with improved morphology, reduced electrode resistance and Ohmic loss.

We used an optical heterodyne detection system to characterize our device.[10,13] This is a very sensitive method, independent of detector response, to characterize the electro-optic phase modulation at high frequencies. As the detector is illuminated by the phase modulated light mixed with a second laser, it generates a photocurrent:

$$i_D \propto \sqrt{I_1 I_2}\{J_0(\phi_1')\cos(\Delta\omega t+\Delta\phi)-J_1(\phi_1')\sin[(\Delta\omega+\Omega)t+\Delta\phi]-J_1(\phi_1')\sin[(\Delta\omega-\Omega)t+\Delta\phi]\}, \quad (1)$$

where I_1 and I_2 are the intensities of the lasers, J_0, J_1 are zeroth and first order Bessel functions of the first kind, ϕ_1' is the phase modulation amplitude, $\Delta\omega$ is the frequency offset of the two lasers, and Ω is the millimeter wave modulation frequency. The last term in Eq. (1) is the downconverted heterodyne signal. For small signal operation

$$J_1(\phi_1') \cong \frac{\phi_1'}{2} = \frac{\pi n^3 r_{33} l}{2\lambda h} V \propto V. \quad (2)$$

As shown in Eq. (1), the optical heterodyne technique is used to downconvert the high frequency optical phase modulated signal (~100 GHz) into a strong low frequency electrical amplitude modulated signal (~3 GHz) requiring only a low speed photodetector. Equation (2) indicates that the heterodyne signal is proportional to the phase modulation amplitude.

Figure 1 shows the high frequency electro-optic phase modulator characterization setup. A 1.319 μm laser beam from a fine tunable Ligthwave Electronics 122 YAG laser was coupled into the end of a single mode optical fiber, with the other end of the fiber cleaved. This cleaved end was brought very close to the input end of the optical waveguide of the device, using a piezoelectric translation stage, and the

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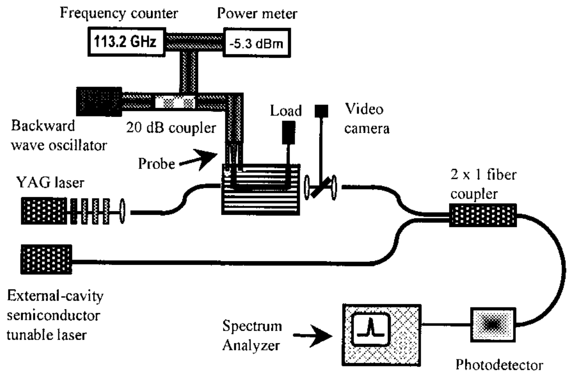

FIG. 1. Optical heterodyne setup for *W*-band electro-optic modulator characterization, a coplanar probe was used to couple the millimeter wave into the device, and an external-cavity semiconductor tunable laser was used to extend the detection frequency range.

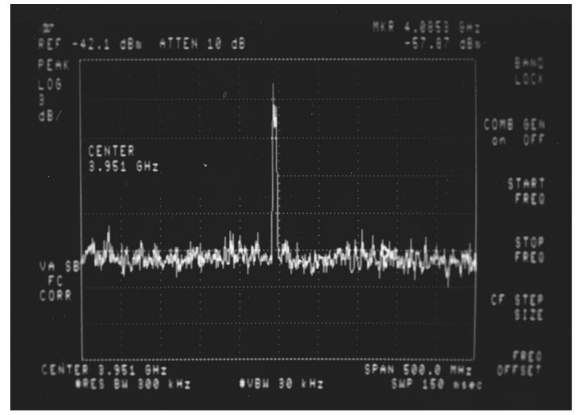

FIG. 2. Polymer modulator optical response at 105.8 GHz, optically down-converted to 3.9 GHz. The device was driven by a *W*-band backward wave oscillator.

light was directly butt coupled into the device. The modulated light output was then collected by a 20× microscope objective and fed into a single mode fiber through another 10× microscope objective. An Environmental Optical Sensors external-cavity semiconductor laser at 1.3 μm with a coarse tuning range of $\sim$8 THz was used for the second beam of the heterodyne detection system. The two beams were combined through a 2×1 fiber coupler, rather than in free space, to reduce optical losses and to increase the optical alignment stability. Next, the combined beams were fed to a Fermionics photodetector, which can response up to 20 GHz. The output of the detector was amplified and displayed on an HP 8592 spectrum analyzer.

At first, the two lasers were turned on and an HP 70950B optical spectrum analyzer was used to find the wavelengths of the two lasers. We tuned the YAG laser frequency to the middle of its range, and tuned the external-cavity semiconductor laser so that the laser frequency offset was approximately equal to the intended millimeter wave modulation frequency. The tuning resolution of the external-cavity semiconductor laser was 1.7 GHz, and its power was set to 0.5 mW. When the millimeter wave power was turned on, the heterodyne signal appeared at low frequency on the spectrum analyzer. Fine tuning of the YAG laser brought the heterodyne signal to the desired preset frequency. When we changed the driving millimeter wave frequency, we also tuned the YAG laser frequency by the same amount so that the signal on the spectrum analyzer was always at the same reading to ensure a simple and reliable calibration. When the fine tuning YAG laser reached its maximum tuning range, we coarse tuned the external-cavity semiconductor laser to extend the frequency measurement range. Unlike the YAG laser, the external-cavity semiconductor tunable laser was not very stable in frequency with its frequency jumping about 100 MHz. The measurement span had to be increased to accommodate such a large drift and the noise floor was raised, thereby compromising the measured signal-to-noise ratio. Even in using these unlocked lasers, the signal was still quite high, due to the reduced optical insertion loss of our new devices.

Before we started to characterize our modulator at *W*-band frequencies, we tested the device at 61 GHz to repeat our previous 60 GHz performance[10] with *V*-band coplanar probes. Using *W*-band coplanar probes, we first observed the *W*-band phase modulation from the polymer modulator by using narrow band Gunn oscillators, which were relatively low noise and had about 20 mW output power at 94 GHz. Later we used several backward wave oscillators (BWO) as the microwave source to systematically characterize the device over the whole *W* band, and a typical measurement at 105.8 GHz is shown in Fig. 2. The BWOs were broadly tunable with output power levels ranging from a few mW up to 50 mW. A power meter and a frequency counter were used to closely monitor the millimeter wave driving power. After normalization for the millimeter wave driving power the device's optical response at different frequencies was plotted. As shown in Fig. 3, from 74 to 113 GHz, the device's optical response was characterized every 1 GHz, and exhibited a maximum variation of 3 dB. This 3 dB included the probe's frequency dependent coupling efficiency. The device's frequency characterization range was only limited by the commercial probe frequency response capability. Such a smooth response validated our predictions that the nonlinear electro-optic polymer materials work extremely well at high frequencies. Combined with our previous work at lower frequencies,[10] the current measurements indicate that these devices can operate effectively over the entire

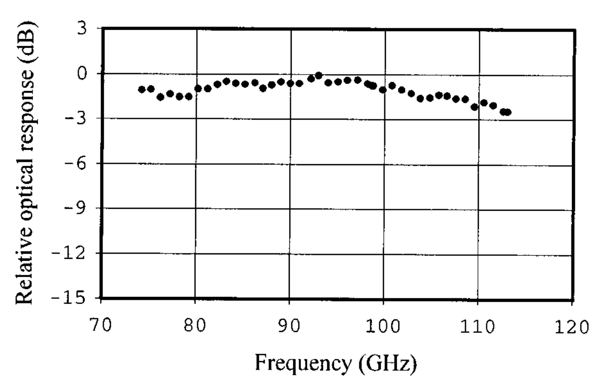

FIG. 3. High frequency optical response curve of the polymer modulator from 74 to 113 GHz. The total variation was less than 3 dB.

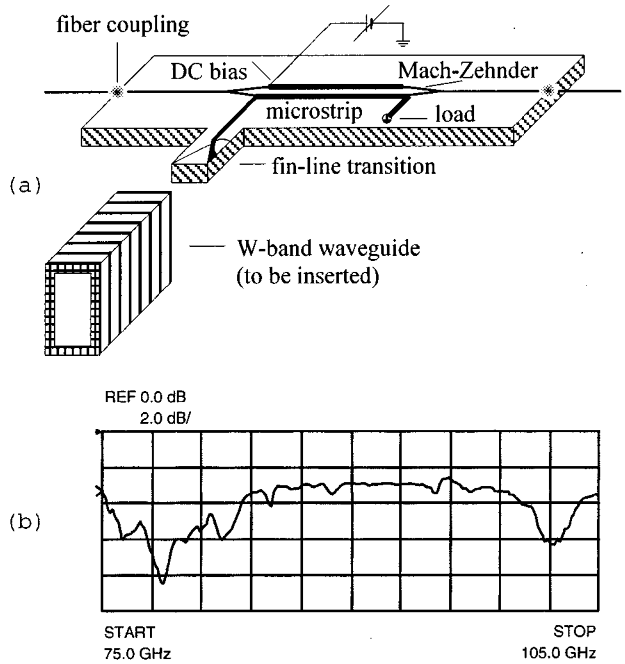

FIG. 4. (a) Overview of the device with an integrated *W*-band antipodal fin-line transition. The transition section is to be inserted into the microwave waveguide for high speed device operation. (b) Measured *W*-band S_{21} of a test circuit.

range from 0 to 110 GHz. Also, on the high frequency plot no resonance appears, indicating that the coplanar probes were well matched to the microstrip lines on the devices.

Based upon these prototype demonstrations, we wanted to develop more robust, less costly devices which do not require the use of commercial rf probes. We have designed and made fin-line structures to effect the monolithic transition between our *W*-band microwave waveguide sources and various electrode configurations on the device. As shown in Fig. 4(a), such transitions gradually transformed the electric field profile and the impedance of the millimeter wave waveguide to that of the microstrip line electrode. Figure 4(b) is the measured *W*-band S_{21} of our test circuit for these monolithic modulators, fabricated on a Duroid 5880 substrate, and consisting of two antipodal fin-line transitions and a 4 cm long microstrip line.

In addition to our effort in extending our modulator's frequency response, processing parameters have now been well characterized and optimized to reduce the optical insertion loss. Furthermore, a new tapered guide technique to make an optical mode match between optical fiber and device optical waveguide has been developed, so that our optical insertion losses can now be reduced to less than 5 dB. Integration of the polymer modulator with various semiconductor drivers on a single chip has also been studied in detail.[14]

In conclusion, we have successfully fabricated and characterized the electro-optic polymer modulators up to 113 GHz. Other key figures of merit including transmission efficiency have also been improved. These devices work at extremely high frequencies, can be configured with integrated microwave transitions, and can be easily fabricated into arrays, having both parallel and series configurations. They will provide an inexpensive alternative to conventional devices, and offer exciting new application areas.

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