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Electro-optic measurement of standing waves in a GaAs coplanar waveguide

Z. H. Zhu,[a] C. L. Pan,[b] Y. H. Lo, M. C. Wu, and S. Wang
Department of Electrical Engineering and Computer Sciences and Electronics Research Laboratory, University of California, Berkeley, California 94720

B. H. Kolner and S. Y. Wang
Hewlett-Packard Laboratories, Palo Alto, California 94304

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We have successfully measured, for the first time, standing waves in a GaAs coplanar waveguide at frequencies of 8.2107 and 12.310 GHz by using harmonic-mixing electro-optic probing. The technique is nondestructive and has great potential in expanding the measuring frequency band to millimeter wave. This letter describes the principle of the technique, the experimental setup, and the measurement results.

In recent years, many exciting applications of the linear electro-optic effect as a measurement technique have been explored. The electro-optic sampling technique has been applied to detect the transients of ultrafast electronic and optoelectronic devices.[1,2] More recently, cw electro-optic probing (CWEOP) has been used to measure the potential profile, field, and charge distribution in GaAs material and devices.[3–5]

In GaAs microwave integrated circuits, a standing-wave electric field will be established in a waveguide if the impedance of the load is mismatched to the characteristic impedance of the waveguide. Therefore, in principle, the electro-optic probing technique can be applied to detect the distribution of standing-wave fields in GaAs microwave waveguides.

Based on this idea, we have successfully measured, for the first time, the distribution of a standing-wave field formed in a GaAs waveguide using a new technique, harmonic-mixing electro-optic probing. The principle of the technique, the experimental setup, and results are presented in this letter.

Conventional slotted line techniques become impractical at high microwave frequencies in waveguides. No technique exists for monolithic microwave transmission lines. Here we employ the harmonic-mixing electro-optic probing to overcome these difficulties. Briefly, when a laser pulse train from a mode-locked YAG laser, modulated by an electric field, illuminates a photodetector, the photocurrent produced by the photodetector is proportional to the product of the light intensity and the modulating voltage. The modulator (GaAs coplanar waveguide sample in our case)-photodetector combination can be viewed as a mixer. In the frequency domain, any signal at frequency f_m propagating in the waveguide will mix with all harmonics of the fundamental repetition frequency f_0 of the mode-locked laser pulse. Sidebands will appear at frequency $nf_0 \pm f_m$. The mixing current is given by[6]

$$i_{\text{mix}} = i_{\text{avg}} \pi \frac{V_m}{V_\pi} \sum_{n=1}^{\infty} \left(\frac{\sin(\pi n f_0 \tau)}{\pi n f_0 \tau} \right) \times [\sin 2\pi(nf_0 + f_m)t - \sin 2\pi(nf_0 - f_m)t], \quad (1)$$

where i_{avg} is the average photocurrent, V_m is the amplitude of the modulating voltage, V_π is the half-wave voltage of the GaAs modulator, n is the order of harmonic component, and τ is the pulse width of the mode-locked laser. Insofar as the mode-locked laser as a local oscillator is concerned, the only requirement is to select a proper frequency f_m of rf signal, then we can easily measure the mixing electro-optic signal at an intermediate frequency f_i, which is given by

$$V_0 \propto i_{\text{avg}} \pi (V_m / V_\pi) R_L, \quad (2)$$

where V_0 is the electro-optic peak voltage developed across a load resistor R_L, and is proportional to the modulating voltage V_m.

The experimental setup is shown in Fig. 1. A laser pulse train of about 10 ps duration at a repetition rate of $f_0 = 82$ MHz is generated by the compressed output of a cw mode-locked Nd:YAG laser ($\lambda = 1.06\ \mu$m). The quarter-wave plate introduces a phase shift of $\pi/2$ between the "fast" and "slow" components of light, so that the electro-optic modulator (i.e., the GaAs waveguide sample) operates in the linear region. The laser beam passes through the GaAs sample and is focused to a diameter of about 8 μm on the central electrode of the coplanar waveguide. The widths of the central electrode, side electrodes, and the spacing between them are 135, 590 and 65 μm, respectively. The rf output with frequency f_m of an oscillator is fed to the GaAs coplanar waveguide (CPW) via a connector (type SMA), and the other terminal of the waveguide is open, so a standing-wave field is established along the waveguide. The laser beam modulated by the standing-wave field is reflected from the electrode, then passes through an analyzer to convert the phase change into amplitude change. A low-speed germanium photodetector is used to detect the mixing signal at the intermediate frequency f_i. A preamplifier is inserted between the photodetector and a spectrum analyzer to optimize the S/N ratio. A TV camera is used to monitor the measuring position exactly. By scanning the laser beam from the open-circuit terminal to the other terminal along the lon-

[a] Permanent address: Department of Radio and Electronic Engineering, Zhejiang University, Hangzhou, China.
[b] Permanent address: Institute of Electro-Optical Engineering, Chiao Tung University, Hsinchu, Taiwan, China.

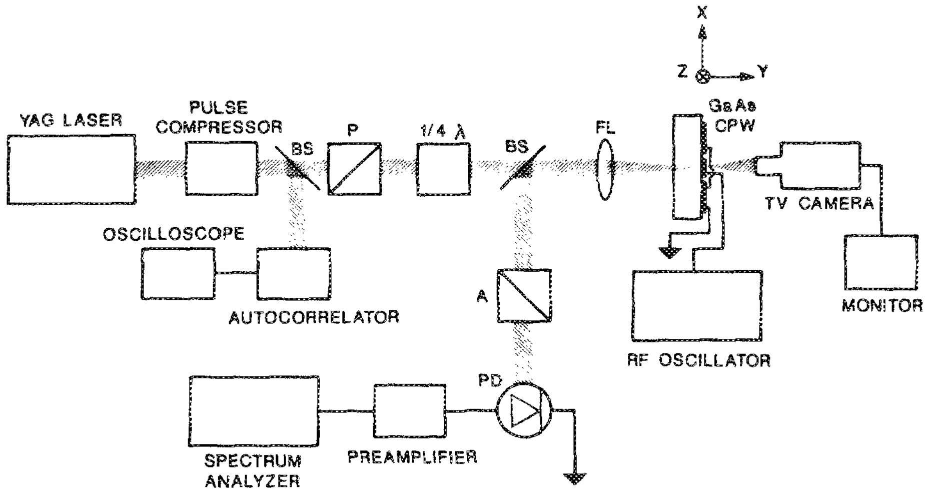

FIG. 1. Schematic diagram of the experimental setup: *P*—polarizer, *A*—analyzer, BS—beamsplitter, FL—focusing lens, PD—photodetector.

gitudinal ⟨011⟩ direction (z axis in Fig. 1) of the CPW electrode, we can detect the standing-wave pattern.

Figure 2 shows the harmonic-mixing electro-optic signal displayed on the spectrum analyzer by mixing the rf signal ($f_m = 8.2107$ GHz) with the 100th harmonic component ($n = 100$) of the fundamental repetition rate ($f_0 = 82$ MHz) of the mode-locked pulse. The intermediate frequency f_i of the mixer signal is equal to 10.7 MHz. The corresponding standing-wave pattern measured is given in Fig. 3. The zero of the abscissa corresponds to the point where the measurement began, but it should be pointed out that the real zero point corresponding to the edge of the open terminal of CPW locates at about 45 mil ($\simeq 1.14$ mm) to the left of the zero of the abscissa. From the pattern we can see that the distance λ_{sw} between valleys is about 270 mil ($\simeq 6.9$ mm) which is equal to the half-wavelength of the rf signal. Substituting these data into the following well-known formula for evaluating the effective index n_e of GaAs CPW,

$$n_e = c/2\lambda_{sw} f_m, \tag{3}$$

where c is the speed of light in air, we get $n_e = 2.65$, which is in good agreement with the value used in the design of microwave GaAs integrated circuits. Similar measurement at the rf frequency of 12.310 GHz (by mixing with the 150th harmonic component of the fundamental repetition rate $f_0 = 82$ MHz of mode-locked pulse) yields $\lambda_{sw} = 180$ mil ($\simeq 4.6$ mm). This is in excellent agreement with the value of λ_{sw} as evaluated using $n_e = 2.65$. From the measured standing-wave pattern, we can evaluate the voltage standing-wave ratio (VSWR) ρ and the reflection coefficient Γ of the GaAs CPW, the result is as follows: $f_m = 8.2107$ GHz, $\rho = 5.97$, $\Gamma = 0.71$; $f_m = 12.310$ GHz, $\rho = 7.94$, $\Gamma = 0.78$. The reason for $\rho \neq \infty$ can be attributed to fringing field capacitance at the end of the transmission line and electrode losses.

In summary, we have successfully measured the standing-wave pattern in a GaAs coplanar waveguide at frequencies of 8.2107 and 12.310 GHz by using harmonic-mixing electro-optic probing. The experimental results are in agreement with the theory and the reproducibility of the measurement is excellent. The technique is reliable and noninvasive. Since the input bandwidth of this technique easily exceeds 100 GHz for picosecond mode-locked pulses, we believe in the near future the technique can be developed to become a standard in making noncontact on-chip measurement of standing waves in GaAs millimeter wave integrated circuits.

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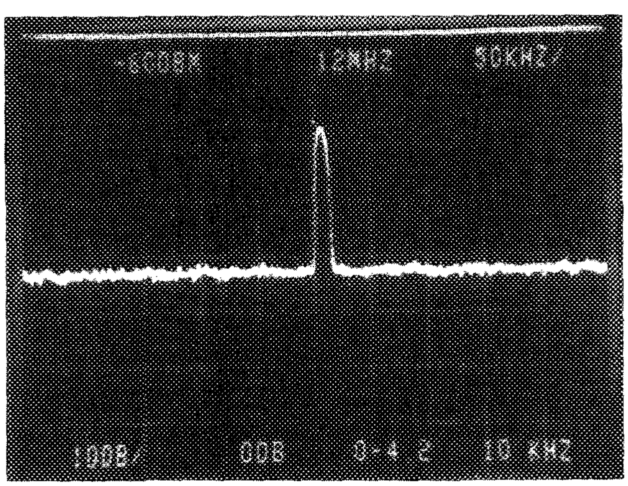

FIG. 2. Harmonic-mixing electro-optic signal ($f_m = 8.2107$ GHz, $f_0 = 82$ MHz, $n = 100$, and $f_i = 10.7$ MHz).

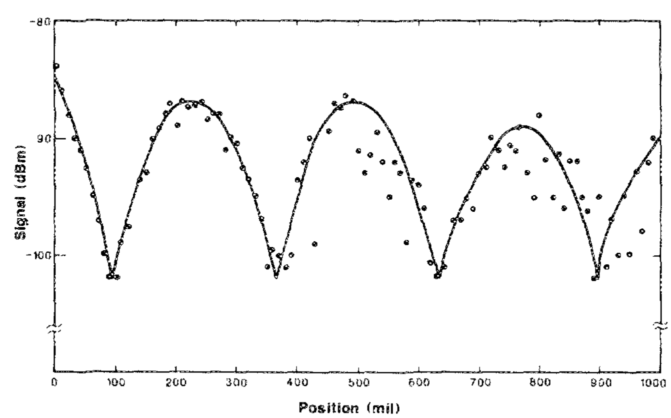

FIG. 3. Standing-wave pattern in GaAs CPW with an open terminal ($f_m = 8.2107$ GHz, $f_0 = 82$ MHz, $n = 100$, and $f_i = 10.7$ MHz).

relator, respectively. The work is supported in part by National Science Foundation grants ECS-8318682 and ECS-8410838, and in part by Joint Services Electronics Program-F49620-84-C-0057.

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