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Measurements on standing waves in GaAs coplanar waveguide at frequencies up to 20.1 GHz by electro-optic probing

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We report the experimental results of the standing waves in GaAs coplanar waveguides at frequencies up to 20.10 GHz with different terminations (open, short, and 50 Ω) by a new electro-optic probing technique. The effective refractive indices from 4.11 to 20.10 GHz are presented and compared with theoretical values. Dispersion of coplanar waveguide in that frequency range is shown to be negligible.

Coplanar waveguide (CPW) is an important component of monolithic millimeter-wave integrated circuits (MMIC) because it is planar, easy to connect shunt devices, and relatively insensitive to substrate thickness variation. The effective refractive index (or guided wavelength) and the waveguide impedance are the most important design parameters. The standing-wave pattern not only can give the exact value of guided wavelength, but also provides useful information about the impedance mismatch between different waveguides, waveguide transitions, discontinuities, and bendings. However, their direct observation by conventional methods is very difficult in microwave or millimeter-wave ranges. The electro-optic sampling technique provides a very powerful tool to measure the transients of ultrafast electronic and optoelectronic devices.[1,2] It has been employed to measure the standing waves[3] and electric field profiles[4,5] in GaAs coplanar waveguides. Some measurement results of standing waves in microstrip lines have also been presented.[6] Here we extend our measurement of standing waves in GaAs coplanar waveguides to 20.10 GHz. Different terminations (open, short, and 50 Ω) to CPW are used for comparison. The experimental data of the effective refractive index are given and compared with theoretical values.

The experimental setup, as shown in Fig. 1, is similar to that in Ref. 1. The cw mode locked Nd:YAG laser ($\lambda = 1.06$ μm) (YAG denotes yttrium aluminum garnet) produces a pulse train of repetition rate $f_0 = 82$ MHz. The sample under test is a GaAs CPW with various terminations. The standing wave is builtup by feeding the CPW with an rf signal of frequency f_m through an SMA connector. The laser beam is focused on the center electrode of the CPW from the backside, and the reflected signal, modulated by the standing-wave field, is detected. The high-order harmonics of the 82-MHz optical signal is mixed with the rf signal. A low-speed germanium photodiode and a spectrum analyzer are used to observe the mixed signal of intermediate frequency f_i. By scanning along the CPW, a standing-wave pattern is obtained. Since the strength of the harmonics around f_m is approximately proportional to $\sin(\pi f_m \tau)/(\pi f_m \tau)$, a short optical pulse width τ is very important for large S/N ratio and higher frequency measurement. Therefore, a pulse compressor is inserted between the laser source and the sample to reduce the pulse width to 3 ps. The CPW under test consists of a center electrode 130 μm wide and two ground planes on either side. With the gap width of 65 μm between the center electrode and ground planes, the waveguide has an impedance of about 50 Ω. The thickness of the GaAs substrate is 500 μm.

The measurements of standing waves were made at several rf frequencies. Figures 2(a)–2(c) show the standing-wave pattern of GaAs CPW with open termination at 12.31, 16.41, and 20.10 GHz, respectively. To compare the reflection coefficients of CPW with different loads, the standing-wave patterns of open, short, and 50-Ω terminations at 16.41 GHz are shown in Figs. 3(a)–3(c), respectively. It should be noted that the physical position of the termination is not accessible to the probing beam; therefore, the absolute zeros of abscissa in both figures are not known. The standing-wave patterns shown in Fig. 3 are aligned with the position of minimum for comparison. The voltage standing-wave ratios ρ and the reflection coefficients Γ calculated from these curves, including those published previously,[3] are listed in Table I.

From these data, first we can see that the values of the voltage standing-wave ratios ρ and the reflection coefficients Γ decrease with increasing frequency due to the higher losses and larger parasitic effects at higher frequencies. Second, the ρ and the Γ with short termination are larger than those with open termination at 16.41 and 20.10 GHz, while they are not much different at 4.11 GHz. This indicates that ideal open is more difficult to obtain than ideal short at high frequency due to radiation loss. The ρ and Γ of the 50-Ω load are reasonably lower than those of open and short terminations.

From these experimental data, we can also obtain the wavelength of standing wave λ_{SW} from 4.11 to 20.10 GHz. Therefore, the effective dielectric constant $\epsilon_{\rm eff}$ and refractive

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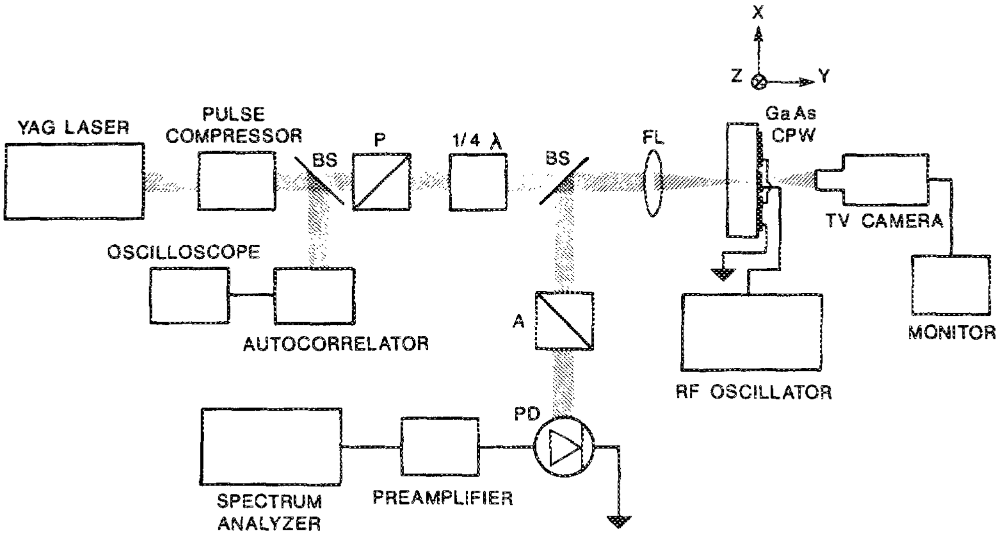

FIG. 1. Schematic diagram of the experimental setup: *P*: polarizer; *A*: analyzer; BS: beam splitter; FL: focusing lense; PD: photodetector.

index $n_{\rm eff}$ can be calculated from $\lambda_{\rm SW}$. They are summarized in Table II. We can see from Table II that the variation of $n_{\rm eff}$ is about 1%, which is within the error of measurement. The experimentally deduced value $n_{\rm eff}$ can be compared with the theoretical value $n'_{\rm eff}$ from the empirical formula,[7]

$$n'_{\rm eff}(f) = \sqrt{\epsilon_{\rm eff}(f)}$$
$$= \sqrt{\epsilon_1} + [(\sqrt{\epsilon_r} - \sqrt{\epsilon_q})/(1 + aF^{-b})],$$

where ϵ_q is the effective dielectric constant at the quasistatic limit, ϵ_r is the dielectric constant of GaAs, $F = f/f_{\rm TE}$, and $f_{\rm TE} = c/(4h\sqrt{\epsilon_r - 1})$. a and b are constants depending on the configuration and dimensions of the sample. In our case, the values of these parameters are as follows: $\epsilon_r = 13$, $\epsilon_q = 6.840$, $f_{\rm TE} = 43.3$ GHz, $a = 24.81$, $b = 1.8$, $c = 3 \times 10^{10}$ cm/s, and $h = 500\ \mu$m (substrate thickness). The experimental and theoretical values agree very well

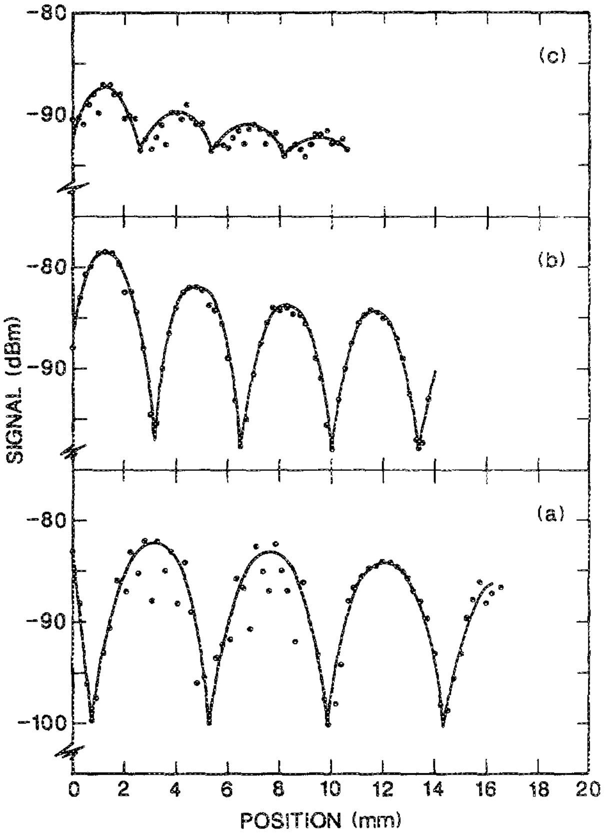

FIG. 2. Standing-wave patterns in GaAs coplanar waveguide with open termination at frequencies of (a) 12.31 GHz, (b) 16.41 GHz, and (c) 20.10 GHz.

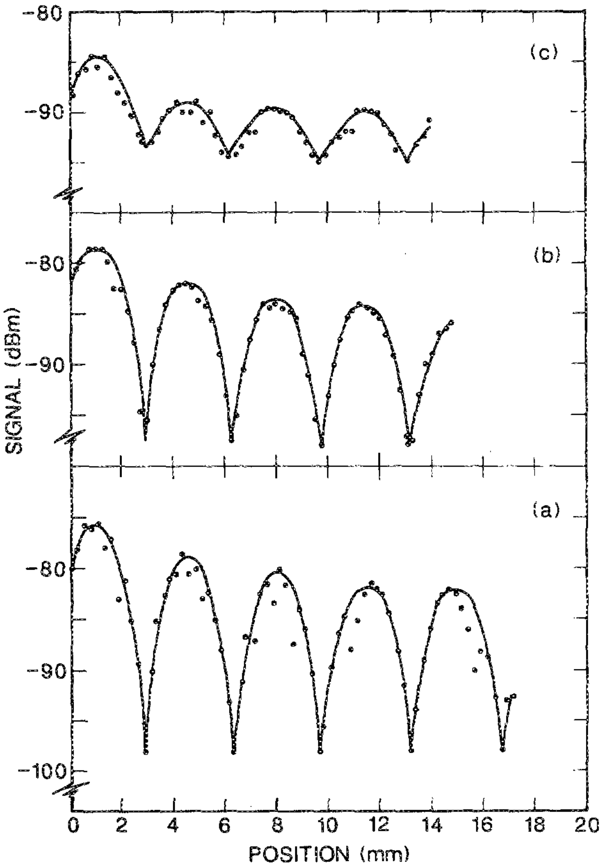

FIG. 3. Standing-wave patterns in GaAs coplanar waveguide with (a) open, (b) short, and (c) 50-Ω terminations at 16.41 GHz.

TABLE I. Voltage standing-wave ratio ρ and reflection coefficient Γ at frequencies up to 20.10 GHz.

f_m (GHZ)	ρ	Γ	Termination
4.11	12.4	0.85	open
	12.6	0.85	short
8.21[a]	5.97	0.71	open
12.31	7.94	0.78	open
16.41	5.95	0.71	open
	9.41	0.81	short
	1.90	0.31	50 Ω
20.10	2.12	0.36	open
	4.0	0.60	short

[a] Data obtained from another sample with same geometry.

TABLE II. Standing wavelength $\lambda_{\rm SW}$, effective dielectric constant $\epsilon_{\rm eff}$, and index of refraction $n_{\rm eff}$ at frequencies from 4.11 to 20.10 GHz.

f_m (GHz)	$\lambda_{\rm SW}$ (mm)	$\epsilon_{\rm eff}$	$n_{\rm eff}$	$n'_{\rm eff}$
4.11	13.60	7.20	2.68	2.616
8.21	6.90	7.01	2.65	2.617
12.31	4.60	7.02	2.65	2.619
16.41	3.45	7.02	2.65	2.622
20.10	2.80	7.10	2.67	2.625

from 4.11 to 20.10 GHz. From these data, we conclude that the dispersion of coplanar waveguide is negligible in this frequency range and that $n_{\rm eff} = 2.66 \pm 0.01$ is obtained for our sample.

In summary, we have made the measurements of standing waves in GaAs coplanar waveguide with different terminations (open, short, and 50 Ω) at frequencies from 4.11 to 21.10 GHz, and presented, for the first time, the complete experimental data of the effective dielectric constant in such frequency range. The dispersion of coplanar waveguide in this frequency range is shown to be negligible for our sample.

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On dose correction in electron beam lithography

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Ideal proximity exposure compensation is shown to occur when the dose correction factors are obtained by considering the electron energy dissipation distribution at the lowest plane in the resist. In such an ideal situation, the simulation of resist profiles in line patterns shows that the resist edge slope becomes nearly equal to what can be obtained with a single beam line.

Proximity exposure in electron beam lithography causes large linewidth variation and unsharp resist edge slope. This is due to the fact that the electron energy dissipation (EED) distribution at different depths in the resist gets wider from top to bottom. A typical EED distribution at different depths in 0.8-μm PMMA on a silicon substrate is shown in Fig. 1 for a 20 keV single electron line source. This distribution is obtained by using an f77 program RESIS[1] based on the Monte Carlo simulation technique, as described earlier.[2]

EED distribution corresponding to the gaussian electron beam is obtained by numerical evaluation of one-dimensional convolution integral given by

$$\frac{\text{No}}{\sigma\sqrt{2\pi}}\int_{-\infty}^{\infty}\exp\left(\frac{-x'^2}{2\sigma^2}\right)I(x-x')dx', \qquad (1)$$

where $I(x)$ is the EED distribution at a given depth in the resist, σ is the standard derivation of the normalized gaussian beam of radius $\sigma\sqrt{2}$, and No is the line charge density (No. of e/cm).

Resist profiles in a 0.8-μm-wide line made up of five single beam lines, a beam diameter of 0.2 μm, a beam-to-