Optical Control of Microwave-Integrated Circuits Using High-Speed GaAs and Si Photoconductive Switches

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***Abstract*—An optoelectronic attenuator suitable for the optical control of microwave-integrated circuits is presented. High-speed photoconductive switches are embedded in planar microwave transmission lines fabricated on both semi-insulating GaAs and high-resistivity silicon substrates, and a fiber pigtailed semiconductor laser diode is used to control the microwave signal level on these high-speed lines. Forty-five dB of microwave attenuation was demonstrated with a silicon coplanar waveguide-photoconductive switch, while up to 8.5 dB of attenuation was achieved with a GaAs device. In addition, the optically induced phase delay through the silicon device was observed to be as large as 180°. The microwave performance of these photoconductive devices has been fully characterized and their suitability for various optical control applications compared. So that one can optimize the laser diode/GaAs photoconductive device interaction, the GaAs device has been characterized as a function of laser photon energy, switch temperature, and applied dc electric field, and the optimum operating point has been determined through experiment.**

I. Introduction

THE USE OF optoelectronic techniques to control microwave circuits and systems continues to be an area of intense research and development [1], [2]. Besides the inherent speed advantages of this approach, the use of a laser to control multiple microwave circuits permits both a high degree of electrical isolation between the control signal and the microwave circuit and timing precision that can easily be in the picosecond regime [2]. This is in addition to the inherent noise immunity of optical fibers.

An optoelectronic attenuator scheme suitable for controlling microwave-integrated circuits has previously been reported [3], [4]. By optically illuminating one of the gaps of a coplanar waveguide photoconductive switch fabricated on a silicon substrate (Si:CPW-PCS), we demonstrated up to 45 dB of attenuation at 1.7 GHz, using a commercial fiber pigtailed AlGaAs laser diode operating at 800 nm with 143 mW of optical power. This is the highest attenuation ever reported for an optoelectronic microwave attenuator [5], [6]. The vector scattering parameters of the Si:CPW-PCS optoelectronic attenuator have now been measured, and we report up to 180° of phase shift at 3 GHz for 250 mW of laser diode power. For the Si:CPW-PCS device, these performance capabilities can be directly related to the relatively long carrier lifetime in the high-resistivity Si material, which for our material was measured to be on the order of 1–10 μs. This permits very efficient optical charge generation to occur in the Si:CPW-PCS substrate, and thus high solid-state plasma densities can be readily achieved, so that device performance is enhanced while laser diode power requirements are reduced [7]. However, one suffers a speed penalty when using this material for applications where high-speed control is required, since microsecond carrier lifetimes necessarily limit the modulation speed to the kilohertz regime.

Semi-insulating gallium-arsenide (GaAs), with its relatively short intrinsic carrier lifetime of between 1 and 5 ns, is obviously better suited for high-speed applications and has the added benefit of being the material of choice for monolithic microwave-integrated circuits (MMIC's). To increase the photoconductive (PC) frequency response of GaAs, one can employ fairly standard techniques to reduce the carrier lifetime to picoseconds (or even femtoseconds) [8], thus increasing the modulation frequency into the terahertz regime. As has already been demonstrated, quantum-well laser diodes fabricated with the AlGaAs/GaAs material system are ideal compact light sources for PC switching applications such as the optoelectronic attenuator [4]. Since these types of laser diodes operate near the band-gap energy of the GaAs:CPW-PCS (i.e., $h\nu \approx E_g$) the photonic absorption mechanism may be either intrinsic, extrinsic or most probably a combination of both types [9]. Hence, the interaction between this class of laser diode and the GaAs:CPW-PCS must be well characterized before an all-Ga-As based optoelectronic attenuator can be realized.

In this paper we present a summary of the results of an extensive investigation performed to assess the interaction between AlGaAs laser diodes and the GaAs:CPW-PCS [10]. We observed the interaction electrically by measuring the switch on-state resistance, R_{on}. We measured R_{on} not only as a function of laser diode power, but also as a function of PC switch temperature and applied dc bias (i.e., electric field). The temperature was varied so that we could determine if the effective band-gap energy, E_g, could be tuned [11] to optimize the laser diode/PC switch interaction; as shown in Section III, this was indeed the case. Since the electric field across the PC switch conduction region can greatly affect the device's performance, the dependence with electric field was also studied.

Manuscript received January 16, 1995; revised April 15, 1995.

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IEEE Log Number 9413674.

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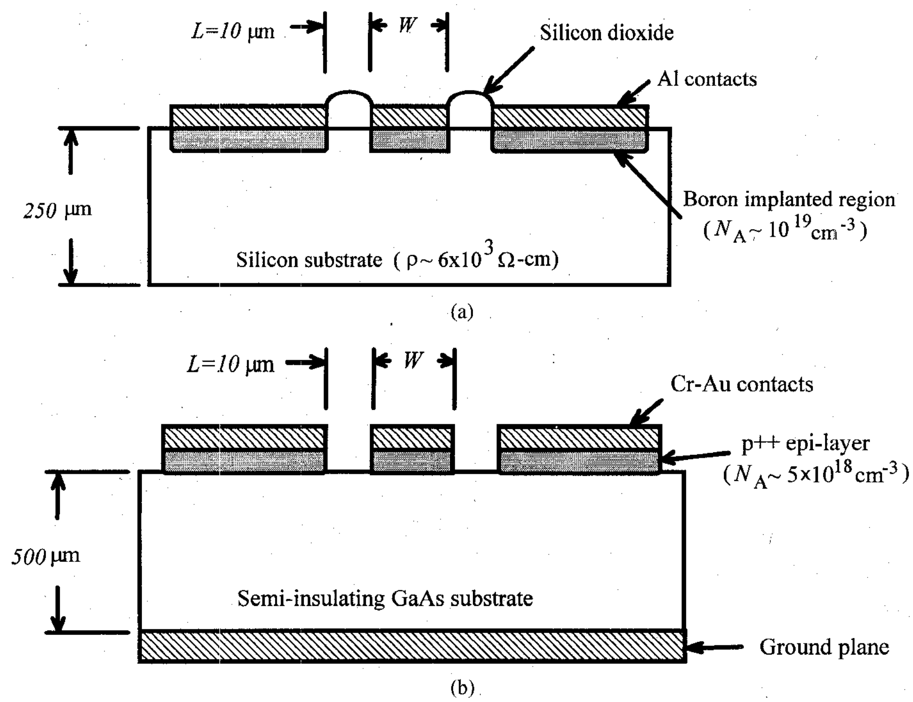

Fig. 1. Cross-sectional view of (a) Si and (b) GaAs:CPW-PCS's. Device length 1.6 cm, $W = 16$ μm.

II. High-Speed GaAs and Si Photoconductive Switches

We designed a coplanar waveguide transmission line to have a characteristic impedance of 50 Ω, with the spacing between the center contact and the two outer (ground) contacts being 5, 10 or 20 μm. Fig. 1 shows a cross-sectional view of both the silicon and GaAs CPW-PCS. The overall device lengths were chosen to be 1.6 cm (see Fig. 4); this length permits switch activation by various laser diode sources, such as linear one-dimensional arrays or multiple discrete broad-area laser diodes.

The silicon substrate thickness was 250 μm with 2500-Å-thick Al contacts deposited to form the coplanar waveguide. The Al contact regions were selectively ion implanted so that ohmic contact was achieved to the high-resistivity ($\rho \approx 6\times10^3$ Ω cm) substrate. Four-thousand Å of SiO_2 were deposited to passivate the surface. The dark resistance (center conductor to ground) for the Si:CPW-PCS was only 13 kΩ, with a center conductor dc resistance of 45 Ω.

The GaAs substrate thickness was 500 μm. A highly doped $p^{++}(N_A \approx 5 \times 10^{18}$ cm$^{-3})$ epitaxial layer was grown by molecular beam epitaxy (MBE) so that ohmic contact to the substrate could be made. Cr-Au contacts (also 2500 Å thick) were then deposited and patterned by a metal lift-off technique, and the epitaxial layer wet chemically etched between the metallizations for electrical isolation. The dark resistance was $\geq$1 MΩ with a center conductor dc resistance of $\approx$15 Ω.

The measured off-state (i.e., dark) insertion loss of the Si:CPW-PCS was 6.5 dB at 500 MHz, while the return loss was typically less than -10 dB. The 45-Ω parasitic center conductor resistance is certainly a contributing factor to this rather high insertion loss; however, the reflected power indicates that the device is otherwise well matched to 50 Ω. The GaAs:CPW-PCS insertion loss was less than 2 dB at 500 MHz (and $\approx$5 dB at 7 GHz), while the return loss was typically less than -15 dB. The reduced insertion loss of the GaAs:CPW-PCS is primarily due to its higher dark resistance (> 1 MΩ), versus the Si:SPW-PCS ($\approx$13 kΩ) as well as to the lower center conductor dc parasitic resistance of 15 Ω. Although these parasitic resistances are a problem for the attenuator application, a gold plating process might be used to greatly reduce it (e.g., 1-μm-thick Au contact would reduce the Si:CPW-PCS parasitic resistance to ~9 Ω). In addition, the rather long device length (1.6 cm) could be reduced to that of the laser diode spot size (typically <3 mm). All attenuation data presented in this paper are normalized to the dark insertion loss; therefore, these parasitic dc resistances do not affect any of the CPW-PCS results described in this paper. In addition, this normalization has the added benefit of permitting direct observation of the optically controlled attenuation.

III. GaAs:CPW-PCS Characterization

In the introduction it was pointed out that AlGaAs/GaAs quantum-well laser diodes are ideal compact laser sources for PC switching applications. Since GaAs PC switches are activated near their band-gap edge when these types of lasers are employed, the switch performance must be fully characterized as a function of laser photon energy so that the laser diode/switch interaction can be understood and optimized. We investigated the laser diode/GaAs:CPW-PCS interaction electrically by measuring the GaAs switch on-state resistance, R_{on}, as a function of incident laser photon energy, switch temperature, and applied dc electric field [10].

To characterize R_{on} versus photon energy, we used a continuous wave (cw) Ti:sapphire laser. The experimental setup used is shown in Fig. 2. The incident power was leveled with a variable attenuator, and the laser wavelength measured

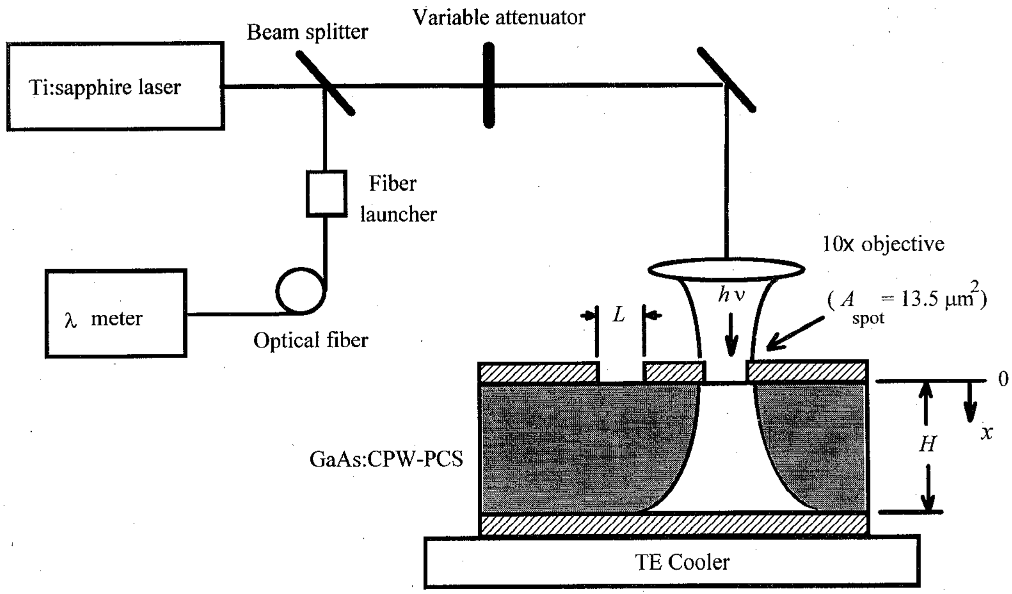

Fig. 2. Experimental setup used to measure $R_{on}(h\nu)$ versus electric field and device temperature. Schematic view of GaAs:CPW-PCS also indicated showing geometrical parameters used in conductive-mode plasma model.

with a wave meter whose accuracy is better than 0.1 nm. A $10\times$ microscope objective was used to focus the incident laser radiation onto one of the GaAs:CPW-PCS switch gaps.

Because the laser was operated in the cw mode, we could use a dc measurement technique to measure R_{on} of the GaAs:CPW-PCW, which was then directly calculated from the measured voltage drop across the switch. Since a high-impedance volt meter ($Z_{in} > 10$ MΩ) was used, the 45-Ω parasitic dc resistance of the center conductor could be neglected. The switch was mounted on a Peltier plate so that the switch temperature could be accurately controlled.

The interaction between the Ti:sapphire laser and the GaAs:CPW-PCS was modeled based on the schematic representation of Fig. 2. This model assumes that the optical field incident on the switch is approximately uniform across the gap, which is valid since only a fraction of the incident gaussian beam covers the switch contacts. Even though below-band-gap radiation is at times employed, we assume that no bulk switching can occur, since the substrate-to-ground-plane contact is not ohmic (experiments on GaAs:CPW-PCS's without ground planes demonstrated that this contact has no effect on the GaAs:CPW-PCS on-state resistance).

The energy band-gap dependence as a function of temperature is given as follows [11]:

$$E_g\ (\text{eV}) = 1.519 - \left\{\frac{5.405\times 10^{-4}T^2}{T+204}\right\}. \quad (1)$$

We used a conductive-mode plasma model [9] to model R_{on} of the GaAs:CPW-PCS, with the on-state conductance given by

$$G_{on} = \left\{\frac{q\mu(1-R)\alpha(hv,\,T)P_{inc}}{L^2hv}\right\} \cdot \int_0^H \frac{e^{\alpha(hv,\,T)x}}{(1/\tau_r + 1/\tau_t(x))\cdot D}\,dx \quad (2)$$

where x is the spatial coordinate indicating the distance from the switch surface and τ_r and $\tau_t(x)$ are the recombination lifetime in the bulk and carrier transit time at the surface, respectively. In particular, $\tau_t(x) = S(x)^2/\mu_s V_b$, where $S = 1+(2x/L)\tan(1.22\lambda/nL)$, n is the refractive index, μ_s is the carrier surface mobility, and V_b is the bias across the switch. The model assumes that the field is constant in the switching gap and equal to half the circuit bias voltage V_c.

The geometrical factor D accounts for the divergence of the optical energy in the substrate, μ is the carrier bulk mobility, R is the optical reflectivity at the surface, L is the switching gap length, and P_{inc} and hv are the incident laser power and energy, respectively. The factor $\alpha(hv,\,T)$ is the energy-dependent absorption coefficient for semi-insulating GaAs [14]; α is also temperature dependent, since a change in temperature causes a shift in E_g, which implies that α must be shifted accordingly. The last parameter in (2) is the substrate thickness H. The on-state resistance R_{on} is then simply the reciprocal of G_{on}.

The recombination lifetimes of the material used in the model were measured to be 5 ns for green (514 nm) light (this is the surface lifetime) and 30 ns for infrared (1.054 μm) light (this is the bulk lifetime). Results from the conductive-mode plasma model are compared with experiment in Fig. 3, where we assume surface and bulk mobilities of 1000 and 8800 cm$^2/V{\cdot}s$, respectively.

Fig. 3(a) shows the dependence of R_{on}, as a function of photon energy, for three values of switch temperature. A 10-μm gap switch was used in these measurements, with 100 mW of incident laser power. Note that the absorption edge tends toward lower energies with increasing switch temperature, as predicted by (1). In particular, at a photon energy of 1.405 eV, a 20°C change in temperature resulted in a threefold decrease in R_{on}.

Fig. 3(b) shows the dependence of R_{on} versus photon energy for several supply voltages. For $V_c = 2$ V, the

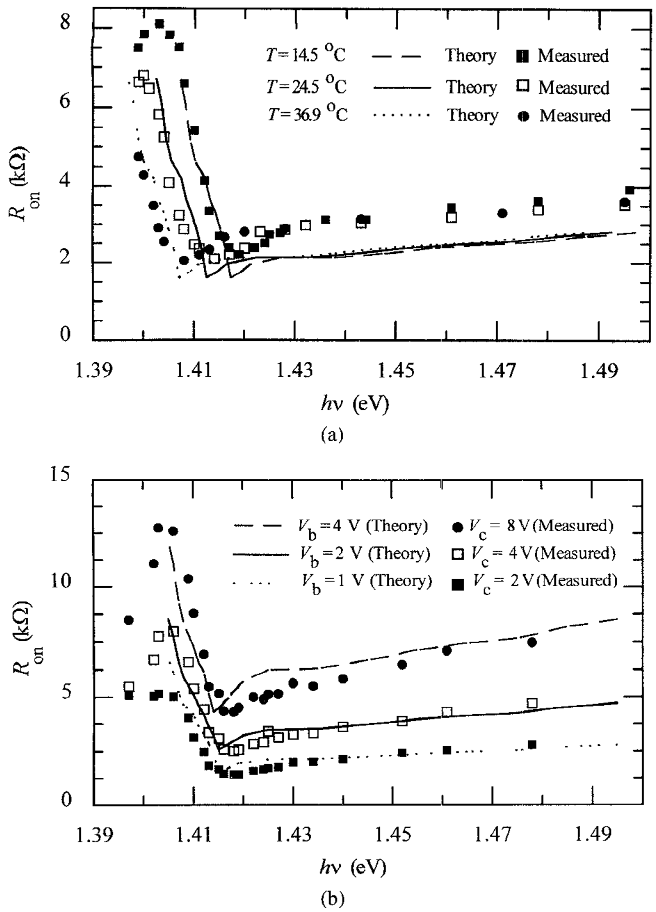

Fig. 3. Conductive-mode plasma prediction of R_{on} as a function of photon energy, $h\nu$, (a) for various temperatures, T; $V_b = 1$ V (theory) and $V_c = 2$ V (experiment); and (b) for various bias voltages, V_c, at $T = 24.5$°C.

resistance variation with incident photon energy follows the absorption coefficient for semi-insulating GaAs: We measure a high resistance for photon energies less than E_g, followed by a large decrease in the resistance for photon energies approaching E_g. The minimum resistance in all cases occurred for photon energies that were slightly less than the expected GaAs band-gap energy ($E_g = 1.430$ eV at 283 K). As the photon energy is increased further, the resistance is seen to gradually increase.

For applied biases of 4 and 8 V, an unexpected peak in R_{on} was observed, as shown in Fig. 3(b). These measurements were repeated for three switches of various gap lengths (5, 10, and 20 μm), which were fabricated on three distinct semi-insulating GaAs wafers. Since this electric-field-dependent peak was observed with each of these devices, the effect appears to be reproducible independent of material variation.

The resistance variation with incident laser power was also measured. With $V_c = 2$ V, the peak in R_{on} was not observed for an incident power of 100 mW; however, it was observed for incident laser power levels of 50 and 25 mW, which naturally correspond to larger R_{on} values and hence a higher applied electric field across the switch. This is fully consistent with the voltage-dependent peak observed in Fig. 3(b) and further substantiates our belief that the behavior is field-dependent.

The experimental variation of R_{on}, as a function of temperature, is within 10 percent of (1), which is within the experimental error of our measurement apparatus. The results of Fig. 3(a) show that one can tune the laser-switch interaction by changing the switch temperature. As an illustration, a laser diode operating at a fixed photon energy of 1.405 eV achieved a GaAs:CPW-PCS R_{on} of $\approx 2\ k\Omega$ at 40°C, whereas the resistance is more than three times this value at 14.5°C. This corresponds to 15 meV of E_g tuning. For comparison, laser diode temperature tuning over the same would change the laser output by less than 6.65 meV, and the tunability is not continuous and predictable.

The dependence of R_{on} for electric fields less than 500 V/cm ($V_c = 0.5$ V) proved to follow the GaAs absorption coefficient, $\alpha(hv)$ for photon energies below and near the band-gap energy E_g. The slope of the resistance versus photon energy curve then increases with increasing energy, since the absorption depth becomes so shallow that surface effects (e.g., decreased carrier mobility and increased carrier recombination from surface defects) start to dominate the conduction process.

For electric fields over 500 V/cm, the high measured R_{on} [Fig. 3(b)] indicates that lower bias voltages are preferable for achieving the minimum possible on-state resistance. Our measurements show that 2 kV/cm is the best biasing field for a 10-μm-gap GaAs:CPW-PCS. Except for the field-dependent peak, the conductive-mode plasma model has accurately predicted the variation in R_{on} for all photon energies. The difficulty in modeling the R_{on} peak may be attributed to the fact that this model does not account for optically induced electric-field distortions within the switching gap.

We had expected to see the velocity overshoot of the low-field mobility in GaAs [12] manifest itself as a reduction of R_{on} for high electric fields; however, the actual fields present during optical excitation are well below those associated with velocity overshoot, and therefore this effect appears not to play a role in the field-dependent peak. Incorporation of velocity overshoot in our model was consistent with this statement. The Franz-Keldysh Effect [13] should manifest itself for high fields as a shift in the absorption edge as a function of photon energy; inspection of Fig. 3(b) indicates that no appreciable shift occurred. In fact, for the fields applied across the switching gap during optical illumination, the estimated shift is on the order of 1 meV, a value clearly within the experimental error of our measurement technique.

IV. Optoelectronic Attenuator Characterization

The scalar scattering parameters of the Si:CPW-PCS have been used not only to characterize the device performance, but also to demonstrate the optoelectronic attenuator scheme [3], [4]. In this section, we summarize previous results to provide the necessary background information for new vector scattering parameter data that have been taken on the Si:CPW-PCS; these new data show that an optically induced phase of 180° is possible at 3 GHz for a laser diode power of less than 250 mW. In addition, new GaAs:CPW-PCS optoelectronic attenuator data are also presented and the performance of this higher speed device contrasted with that of the Si:CPW-PCS.

Fig. 4 shows a schematic view of the optoelectronic attenuator discussed here. A commercially available fiber-pigtailed laser diode was used to optically vary the attenuation of 10-

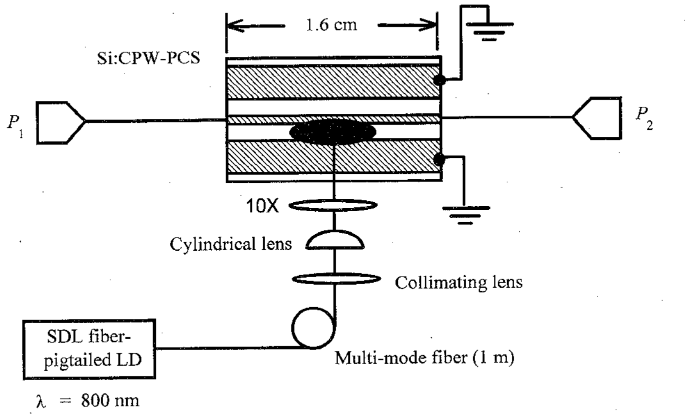

Fig. 4. Fiber-pigtailed laser diode experimental setup used to measure $|S_{11}|$ and $\Delta|S_{21}|$ of hybrid silicon optoelectronic attenuator. P_1 and P_2 denote SNA measurement ports.

MHz to 3-GHz signals through a 10-μm-gap Si:CPW-PCS (the GaAs:CPW-PCS attenuation was also measured with this same technique from 10 MHz–10 GHz).

Two possible attenuation modes may be responsible for the observed attenuation in both coplanar devices: a reflective mode where an optically induced impedance discontinuity reflects the incident wave [4] or an absorptive mode where the wave is attenuated by an optically induced solid-state plasma [15]. Initial pulsed-voltage measurements [3], made at an rf frequency of 500 MHz, showed that 30 dB of optically induced attenuation could be achieved; however, during these initial experiments, we only measured the signal attenuation through, and not the reflected power from, the Si:CPW-PCS. Therefore, the exact nature of the attenuation mechanism remained unclear.

Using an SNA, we measured the magnitudes of both the power reflection from, and the power flow through, the Si:CPW-PCS during optical illumination (i.e., $|S_{11}|$ and $\Delta|S_{21}|$, respectively), as shown in Fig. 5 ($|S_{11}|$ shown is the absolute value, while $\Delta|S_{21}|$ is the value measured minus the dark value, hence the Δ designation). Since the design frequency was 1 GHz, the SNA sweep was limited from 10 MHz to 3 GHz. As the optical power, P_{LD}, was increased, the attenuation through the device increased while the corresponding measure of reflected power decreased; this indicates that the Si:CPW-PCS becomes "better matched" as the optically induced attenuation increases [4]. However, if the mechanism responsible for the observed attenuation were reflective, then this would certainly not be the case (i.e., S_{11} would become more positive on a dB scale); therefore, these data indicate that the attenuation mechanism responsible for attenuation of microwave signals in the Si:CPW-PCS is absorptive.

During SNA characterization, the attenuation saturated to a maximum value of approximately 20 dB (at 3 GHz) when diffraction-limited spherical optics (see Fig. 4) were used to focus the laser beam onto one of the Si:CPW-PCS switch gaps. When the beam profile was expanded along the transmission line, the level of attenuation increased by more than 25 dB above the saturated value [4], as shown in Fig. 6 for a spot size of 10 μm× 3.5 mm. Two important effects were observed

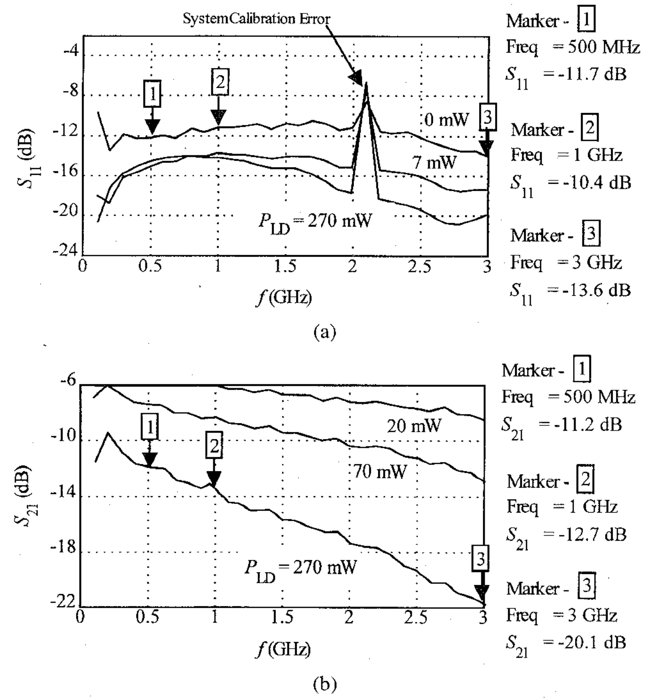

Fig. 5. Si:CPW-PCS SNA data for (a) $A_{spot} = 10\ \mu m^2$, showing absolute return loss, $|S_{11}|$ and (b) optically induced attenuation $\Delta|S_{21}|$ versus optical power, P_{LD}.

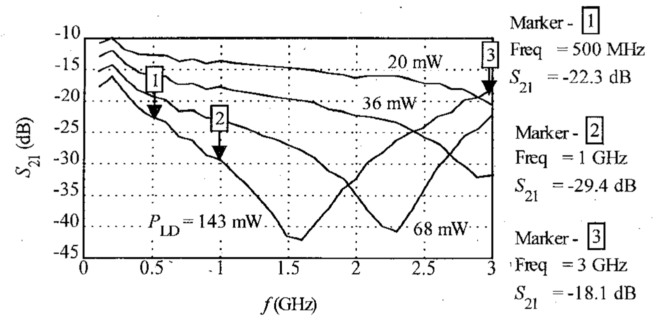

Fig. 6. Si:CPW-PCS SNA data showing optically induced attenuation $\Delta|S_{21}|$ versus optical power, P_{LD}, for $A_{spot} = 10\ \mu m\times 3.5$ mm.

as the beam was expanded: First, the attenuation increased for a fixed laser power. Second, the attenuation became narrow-band, which by itself is not unexpected since the attenuation should be a maximum at the microwave frequency that is equal to the plasma frequency, ω_p [15]. However, as the laser intensity increases, so does the plasma frequency, yet the maximum attenuation tends to lower microwave frequencies. This we attribute to a perturbation of the quasi-TEM coplanar waveguide mode, a point that is presently under further study. What is clear is that we can optically control the absorption level and maintain either a wide-band ($\Delta|S_{21}| < 20$ dB) or a narrow-band ($\Delta|S_{21}| > 20$ dB) attenuation characteristic. By careful adjustment of the beam position, the maximum value of $\Delta|S_{21}|$ measured was 45.6 dB at a frequency of 1.7 GHz for 143 mW of laser diode power.

The optically induced electrical phase delay through the Si:CPW-PCS was characterized with a vector network analyzer (VNA). The measured optically induced attenuation, $\Delta|S_{21}|$, and phase shift, $\Delta\Phi(S_{21})$, for both a 10-μm diffraction-limited and a 10 μm × 3 mm spot, are shown

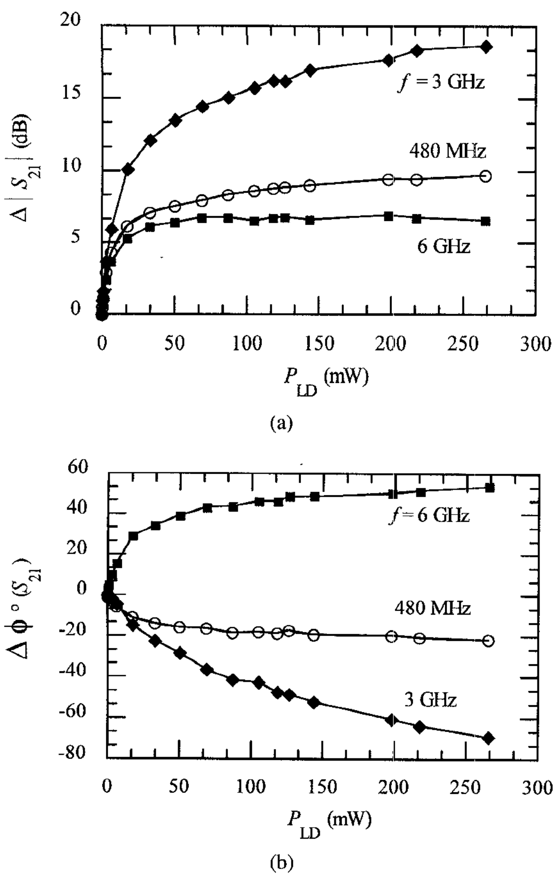

Fig. 7. Si:CPW-PCS VNA data for $A_{spot} = 10\ \mu m^2$, showing optically induced (a) attenuation and (b) phase shift. Note maximum phase shift of $\sim 70°$ at 3 GHz.

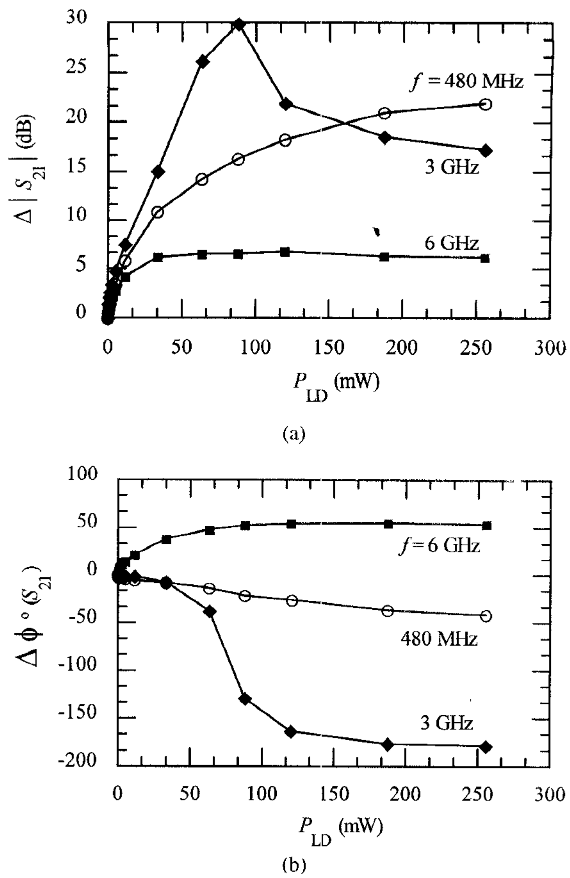

Fig. 8. Si:CPW-PCS VNA data for $A_{spot} = 10\ \mu m \times 3$ mm, showing optically induced (a) attenuation and (b) phase shift. Note maximum phase shift of $\sim 180°$ at 3 GHz.

in Figs. 7 and 8, respectively. The optically induced phase variation is again frequency dependent, with an maximum phase change of 180° observed at 3 GHz, with the expanded laser spot. Note that for a frequency of 3 GHz, $\Delta\Phi(S_{21}) \approx -70°$ with the diffraction-limited spot, and is $-180°$ for the expanded 10 μm $p\times$ 3 mm spot. At 480 MHz, the data implies that $\Delta\Phi(S_{21})$ doubles when the beam is expanded, while at 6 GHz $\Delta\Phi(S_{21})$ decreases slightly in value when the spot size is expanded.

Using the same experimental setup depicted in Fig. 4, we measured the optically induced attenuation through a 5-μm gap GaAs:CPW-PCS using a SNA. Due to the higher-speed inherent for the GaAs:CPW-PCS, the sweep was set for 10 MHz–10 GHz. A maximum attenuation of 8.5 dB was achieved for a laser diode power of 680 mW. Although this result appears to be of little practical interest when compared to the Si:CPW-PCS, one must note several important distinctions between the performance of the two devices: First, the maximum attenuation with the GaAs device is at 7 GHz and not 1.7 GHz, as was the case for the Si device. Second, for some applications, such as high-speed modulators, 8.5 dB of attenuation may be suitable. In addition, the higher dark resistance of the GaAs device has the added benefit of a lower dark-state insertion loss, and hence system performance may prove superior with the GaAs attenuator. Finally, this technique is clearly compatible with standard MMIC's and hence more amenable to monolithic integration with existing MMIC technology.

However, the contrast ratio, defined here as the ratio of the off-state to on-state device resistance, is 1 MΩ: 2 kΩ or 500 for the GaAs device, while the Si device has a contrast ratio of 13 kΩ: 10 Ω, or 1300. Clearly, one needs to consider several factors when designing photoconductive-based devices and subsystems: carrier lifetime (modulation rate and maximum attenuation/laser diode efficiency), off-state resistance (dark insertion loss), and contrast ratio (modulation depth).

V. Conclusion

Using a silicon high-speed photoconductive switch, we have demonstrated up to 45 dB of microwave attenuation at 1.7 GHz using only 143 mW of laser diode power. Recent measurements to characterize the full vector scattering parameters (magnitude and phase) of this device indicate that 180° of optically induced phase shifting is also possible at 3 GHz with 250 mW of laser power. The data show that although the attenuation increases with increasing laser power, and hence plasma density, the peak attenuation actually tends to lower frequencies under these conditions. In fact, the phase delay measured through the silicon devices was negative for frequencies below 3 GHz, and positive for those above this value, in direct contradiction with the Kramers-Kronig relationship [16]. However, our measurements were made in a transmission structure and we believe this explains the apparent contradiction.

We have characterized the behavior of a GaAs coplanar-waveguide photoconductive switch as a function of photon energy, electric field, and temperature. The results of this investigation permit the optimization of the interaction of AlGaAs laser diodes with GaAs PC switches. A conductive-mode plasma model of the CPW-PCS has been developed that predicts the observed GaAs:CPW-PCS temperature and electric field-dependent behavior below 500 V/m. An improved model that takes into account the distortion of the electric field within the gap should result in a quantitative prediction for all field values. More importantly, the device temperature can be used to tune the laser diode/GaAs:CPW-PCS interaction so that an optimum operating point can be achieved without the need for costly laser diode spectral tuning.

The low level of optically induced attenuation in the GaAs:CPW-PCS is mainly attributable to the semi-insulating GaAs substrate used; the long carrier lifetime in the silicon substrate (1–10 μs) compared with the short lifetime in semi-insulating GaAs (1–5 ns) permits more efficient charge generation (and hence higher solid-state plasma densities) to be achieved in the Si:CPW-PCS [7]. However, the GaAs:CPW-PCS demonstrated superior high-speed performance and has the important technological advantage of being more readily integrable with standard MMIC technology. Further, 8.5 dB of attenuation may be adequate for some high-speed modulator applications. The development of an all-GaAs-based design, which would incorporate superlattice structures to permit accurate control of the carrier lifetime to the desired value, is planned. Indeed, the carrier lifetime in GaAs has been greatly increased in photoconductive devices [17], indicating that this may be a viable approach for optimizing the optoelectronic attenaution performance.

VI. Acknowledgment

The authors would like to acknowledge P. Polak-Dingels of the Laboratory for Physical Sciences, College Park, MD, for the Use of her Ti:sapphire laser. We also thank R. Leavitt and A. Balekjian, both of the Army Research Laboratory, for growing the GaAs epi-layers and for assisting in the fabrication of the Si:CPW-PCS devices.

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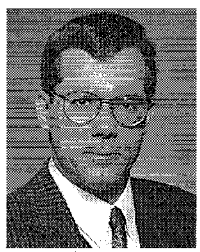

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