Picosecond Pulse Propagation on Coplanar Striplines Fabricated on Lossy Semiconductor Substrates: Modeling and Experiments

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***Abstract*— A simple model for the propagation of high-frequency signals on coplanar striplines with lossy semiconductor substrates is proposed and demonstrated. This model incorporates the effect of a conductive substrate through the loss tangent in a distributed-circuit analysis extended to high frequencies. Very strong attenuation and dispersion due to the substrate are observed even when the GaAs conductance is only 1 mho/cm, corresponding to a doping density of around 10^{15} cm^{-3}. The accuracy of this model is tested with a direct comparison to experimental data of picosecond pulse propagation on a doped-GaAs coplanar stripline (CPS) measured in the time domain using the electro-optic (EO) sampling technique. Good agreement is found in terms of the attenuation and phase velocity of the distorted pulses at four propagation distances up to 300 μm. The pulse propagation on a multiple modulation-doped layer is also studied experimentally as a prototype of high-frequency signal propagation on the gate of a modulation-doped field-effect transistor (MODFET). The attenuation shows linear frequency dependence up to 1.0 THz, contrary to the cubic or quadratic dependence of coplanar transmission lines on low-loss substrates.**

I. Introduction

ADVANCES in microelectronic-device fabrication and physics have pushed the response of high-speed transistors into the multi-hundred gigahertz range (see, for example [1]). Therefore, the characteristics of many planar transmission lines which connect such high-frequency devices within circuits have been, and are still being, extensively studied experimentally and theoretically (see, for general review, [2]). Among the transmission structures considered are microstrip lines [3]–[6], coplanar waveguides [7]–[11], and coplanar striplines [12]–[16]. These investigations are mostly based on lossless or low-loss dielectric substrates, which would typically be intrinsic semiconductors. In those cases, the attenuation largely originates from the ohmic losses of the metal line and the radiation loss, while the dispersion results from the line geometry and the frequency dependence of the effective permittivity of the transmission line. However, the case of signal propagation on a structure utilizing a highly lossy substrate frequently occurs. A typical example is the gate line of a modulation-doped field-effect transistor (MODFET) or metal–semiconductor field-effect transistor (MESFET). The thin, long gate surrounded by the source and drain pads forms a coplanar waveguide fabricated on a highly conductive modulation-doped layer. The distortion of signals in such a device would severely degrade the transistor speed performance. Another example of lossy substrate propagation arises in substrates that have been unintentionally doped during fabrication. Circuit applications using these substrates could lead to unwanted attenuation and dispersion of guided high-speed signals.

An illuminating way to investigate very high-bandwidth transmission lines is to observe the evolution of Gaussian-shaped picosecond electrical pulses guided by these structures. Such numerical and experimental exercises directly demonstrate the extent of signal attenuation and dispersion [13]. Also, with the Fourier transform of the temporal-domain pulses, spectral-domain information can be obtained over a very wide bandwidth, from dc to terahertz [11]. From the experimental point of view, this short-duration-pulse method is the only way to characterize terahertz-bandwidth transmission lines, since conventional frequency-domain systems such as the network analyzer are limited in bandwidth to the tens of gigahertz. Time-domain optical probing methods, such as electro-optic (EO) sampling [17] or photoconductive sampling [18], are thus the only techniques with adequate measurement bandwidths.

In this paper, we model picosecond electrical pulse propagation along a coplanar stripline (CPS) fabricated on highly lossy, conductive semiconductor substrates. The distributed-circuit model, extended up to very high frequencies through the use of frequency-dependent circuit parameters and effective permittivity, is used for this modeling [11], [13]. The effect of substrate loss due to the conductivity is included in the shunt conductivity through the loss tangent of the substrate. This modeling is also verified by pulse propagation experiments on a coplanar stripline on n-doped GaAs, the most common substrate material for high-speed-device fabrication. A fast photoconductive switch on a low-temperature-grown-GaAs substrate [19] and the EO sampling technique [17] are used along with a short-pulse laser to generate and measure the 1-THz signals in the experimental investigation. Furthermore, experimental data of pulse propagation on CPS with a coplanar modulation-doped multiple-quantum-well (MQW) substrate

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are presented. This simulates high-frequency signal propagation on the gate of a high-electron-mobilty transistor (HEMT) fabricated on a modulation-doped layer.

II. Modeling of Coplanar Stripline on Lossy Substrate

A few general and specific aspects of our approach to the modeling of pulse propagation on transmission lines are first presented.

In our computations, a time-domain waveform propagating at a certain point on an arbitrary transmission line has been represented as a voltage signal $V(t,z)$ with a certain time dependence. Considering $V(t,0)$ as the waveform at a spatial origin, a waveform at a point z, $V(t,z)$, is thus given by

$$V(t,z) = \boldsymbol{F}^{-1}[\boldsymbol{F}\{V(t,0)\}\exp\{-\gamma(f)z\}] \tag{1}$$

where $\boldsymbol{F}\{\cdot\}$ denotes the Fourier transform of $\{\cdot\}$, $\boldsymbol{F}^{-1}\{\cdot\}$ the inverse Fourier transform of $\{\cdot\}$, and $\gamma(f)$ the complex propagation factor [13]. The propagation factor consists of real and imaginary parts

$$\gamma(f) = \alpha(f) + j\beta(f) \tag{2}$$

where α and β are the attenuation and the phase factor of the voltage signal, respectively. The former mainly arises from the radiation, conductor, and dielectric losses, where the dielectric loss dominates when the substrate is highly conductive due to, for example, the free carriers in a doped semiconductor substrate. The latter term, which determines the degree of dispersion a signal experiences, is affected primarily by the geometry of the transmission line, its dimensions, and the substrate permittivity.

We have used the distributed-circuit analysis to calculate the propagation factor $\gamma(f)$, with the valid frequency range of the model extended to the terahertz regime using an accurate approximation for the high-frequency permittivity. Although the analysis is based on the quasi-static behavior of the transmission line, a good deal of success has been realized by modifying and applying it to high-frequency propagation. This has been accomplished by including frequency-dependent circuit parameters and empirical information regarding such quantities as the frequency-dependent effective permittivity [13]. Since the explicit relationship between phase factor and frequency is very complicated, leading to rigorous electromagnetic-field analyses requiring substantial amounts of computation time, an alternate approach trading off accuracy to gain practical understanding with quick microcomputer-based numerical simulations was desirable. Hence this rather simplistic extended-distributed-circuit model was followed because it provided rapid results of many propagation situations, facilitating quick comparisons with measured waveforms and leading to an enhanced physical insight of propagation behavior.

The transmission-line circuit parameters are related to the attenuation and phase factor through

$$\gamma(f) = \alpha(f) + j\beta(f) = \sqrt{Z(f)Y(f)} \tag{3}$$

where $Z(f)$ and $Y(f)$ are the series impedance and the shunt admittance of the transmission line, respectively. These are given as follows for the coplanar striplines [13]:

$$Z(f) = j2\pi f\mu_0 g_1 + Z_s(f)g_2 \tag{4}$$

$$Y(f) = 2\pi f\varepsilon_0\{j\varepsilon_{r,\mathrm{eff}}(f) + \varepsilon_r \tan\delta(f)\}/g_1 \tag{5}$$

where f is the frequency, μ_0 and ε_0 are the permeability and permittivity of vacuum, $Z_s(f)$ is the complex surface impedance of the conductor, and $\varepsilon_{r,\mathrm{eff}}(f)$ and ε_r are the effective and relative permittivities of the substrate. The factors g_1 and g_2 are determined by the geometry of the transmission line and are independent of frequency [20].

The frequency-dependent loss tangent, $\tan\delta(f)$, is the quantity that relates the substrate loss with the propagation factor in our investigation. For a semiconductor substrate having free carriers due to doping, the loss tangent can be expressed by

$$\tan\delta(f) = \frac{2\pi f\varepsilon''(f) + \sigma'(f)}{2\pi f\varepsilon'(f) + \sigma''(f)} \tag{6}$$

where ε' and ε'' are the real and imaginary parts of the complex dielectric permittivity given by $\varepsilon = \varepsilon' - j\varepsilon''$. Similarly, σ' and σ'' are the real and imaginary components of the complex conductivity defined by $\sigma = \sigma' - j\sigma''$. However, the dielectric resonances for typical semiconductors, including GaAs, are at frequencies far above the frequency content of the picosecond electrical pulses used in this simulation and experiment [21]. Therefore, ε' can be taken to be constant and equal to the static permittivity, ε'' is negligible, and the loss tangent has a frequency dependence through the frequency-dependent conductivity.

The complex conductivity drawn from the Drude model is given by

$$\sigma = \sigma_s/(1 - j2\pi f\tau_m) \tag{7}$$

where σ_s is the dc conductivity and τ_m is the effective equilibrium momentum relaxation time [22]. σ_s can be obtained from the dc mobility of the majority carriers from Hall measurements using $\sigma_s = ne\mu$, where n is the electron density, e is the electron charge, and μ is the dc mobility of the electrons for the n-doped case. The momentum relaxation time is given by $\tau_m = m^*\sigma_s/ne^2$ where m^* is the effective mass of an electron. With these values for conductivity, the loss tangent is obtained using (6). Inserting the loss tangent into (5), we now have $Z(f)$ and $Y(f)$, which are used to calculate the complex propagation factor $\gamma(f)$ using (3). Particularly note that the propagation factor depends on the product of $Z(f)$ and $Y(f)$, and thus the phase factor maintains a dependence on the shunt losses of the transmission line. Dispersion due to loss, usually very small for the ohmic losses of a typical line and thus ignored, can increase substantially and become significant for a highly lossy line.

In the computed propagation factor, the loss due to radiation has not been considered through the distributed circuit model. However, the radiation loss must be included in the real part of the propagation factor, as it is the dominant loss mechanism when the substrate loss is purely dielectric $(\tan\delta = \varepsilon'/\varepsilon'')$ [23]. The semi-empirical formula of the radiation loss for the coplanar stripline is given by [11], [23]

$$\alpha_{\text{rad}} = \pi^5 \, \frac{(3-\sqrt{8})}{2} \sqrt{\frac{\varepsilon_{r,\text{eff}}(f)}{\varepsilon_r}} \left(1 - \frac{\varepsilon_{r,\text{eff}}(f)}{\varepsilon_r}\right)^2 \cdot \frac{(s+2w)^2 \varepsilon_r^{3/2}}{c^3 K'(k) K(k)} f^3 \tag{8}$$

where s is the separation between the electrodes, w is the width of each electrode, $K(k)$ is the complete elliptical integral of the first kind, and $K'(k) = K(\sqrt{1-k^2})$ with $k = s/(s+2w)$. The propagation factor modified to include the radiation loss is used in (1) to compute time-domain waveforms at different positions.

A. Numerical Examples

A time-dependent Gaussian pulse of 1-ps full-width-at-half-maximum (FWHM) duration was used as the input pulse at a spatial origin, $V(t, 0)$. The pulse had a frequency content with components in excess of 1 THz. To illustrate the effect of the lossy substrate, three different conductivities, 0.0, 0.1, and 1.0 mho/cm, were used in the computations. In the first case the loss tangent and substrate loss only depended on the ratio of the complex to real permittivities, and without a dielectric resonance, this was negligible compared with the loss from the conductor and the radiation from the CPS [23]. This case served as a reference to ones that also included a conductive loss for the substrate.

In these examples, a CPS having an electrode width of 20 μm, an electrode spacing of 10 μm, and an electrode thickness of 3500 Å was assumed to be fabricated on a GaAs substrate. Fig. 1(a) shows the picosecond pulse propagation on the CPS without any conductive loss. Modal dispersion can be clearly seen by the broadening of the rising edge and the negative dip in the tail as the pulse propagates longer than 1 mm. Physically, the coupling of the higher order modes that are present in the open-boundary planar transmission line becomes more efficient for the higher frequency components in the pulse. This implies that a higher flux density exists in the substrate for higher frequencies, so that the effective permittivity increases with increasing frequency. This results in a phase velocity that decreases with increasing frequency, and leads to ringing in the tail of the pulse. Also, some attenuation was observed due to the ohmic loss of the metal lines and the radiation loss. However, the overall attenuation became much stronger when the substrate had a conductance of 0.1 mho/cm, corresponding to a free-carrier doping of around 10^{14} cm^{-3} in GaAs as shown in Fig. 1(b).

The modal dispersion effect was similar to that of the nonconductive substrate case, although the effect was less visible because of the strong absorption. If the conductance of the substrate was further increased to 1.0 mho/cm, the conductive factor totally dominated in the pulse propagation in terms of not only the attenuation, but also the dispersion as shown in Fig. 1(c). The peak amplitude of the pulse decreased to less than 5% after 1-mm propagation. Also, the peak arrived later in time compared to the lower conductance case because the conductance loss now played a more significant role in the

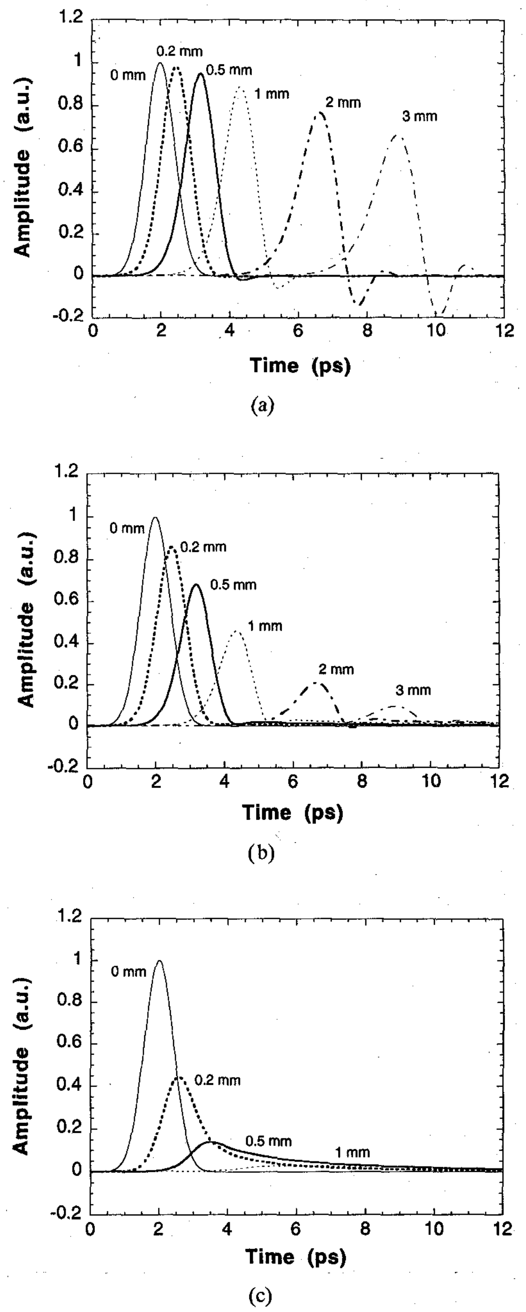

Fig. 1. Temporal evolution of a 1-ps-FWHM electrical pulse propagating on a coplanar stripline, showing distortion due to the attenuation and dispersion for three different substrate conductivities. (a) 0.0, (b) 0.1, and (c) 1.0 mho/cm.

dispersion of the signal. This was more evident in the trailing part of pulse. The tail became very long due to the modal dispersion from the conductance and masked the dispersion due to the transmission-line geometry.

III. Experiment

A. Verification of Modeling

An ultrashort pulse laser was used in the experiments to both generate and sample picosecond electrical pulses. The Gaussian electrical pulses were generated using a photoconductive switching gap fabricated on GaAs grown by MBE at

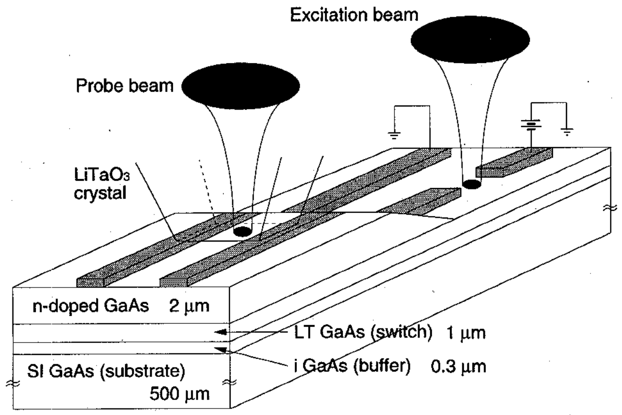

Fig. 2. Diagram of the experimental scheme for the generation and detection of short-duration electrical pulses propagating on a coplanar stripline fabricated on n-doped GaAs. $LiTaO_3$ is an electro-optic crystal used in the sampling of subpicosecond electrical transients via the Pockels effect. The excitation and probe optical beams represent trains of 80-fs laser pulses separated by 10 ns.

$\sim$200°C [19]. Subsequently the propagating electrical transients were measured using the terahertz-bandwidth external EO sampling technique along the transmission-line as shown in Fig. 2 [17], [24]. The transmission lines were deposited and lithographically defined as shown in the figure. The conductive layers under the metal lines were also grown by molecular beam epitaxy (MBE). Half of the top GaAs layer was etched away to provide access to a low-temperature-grown GaAs (LT-GaAs) switch layer. The short-pulse source used here was a self-mode-locked Ti:sapphire laser [25], with a pulse width of 80 fs and a wavelength of 800 nm. The output power of 200 mW was split into the excitation and probe beams for exciting the photoconductive switch and detecting the electric-field transients, respectively. The superior noise characteristics of the Ti:sapphire laser gave us a good signal-to-noise ratio for the EO sampling measurement, as compared with the dye lasers [26] that have been typically used.

The time-domain waveforms measured at several points along the transmission-line are presented in Fig. 3(a). The Hall measurement of this sample showed that the static conductivity of the n-doped layer was 5 mho/cm. The waveform labeled as "0 μm" was measured at a position immediately following the interface of the photoconductive-pulse-generation region and the lossy n-doped region, which we regarded as the origin. This waveform already displayed some effect of dispersion because it was generated at a photoconductive switching gap 500 μm from the n-doped interface. The successive waveforms at four different points demonstrated the very strong absorption due to the high conductance of the substrate. Also, the dispersion due to the substrate conductance became apparent as the pulse propagated.

The experimental input at the spatial origin was input to the simulation code described in the previous section and compared with the experimental results to verify the validity of our modeling. The input parameters used in the simulation were the doping density (10^{16} cm^{-3}), the measured

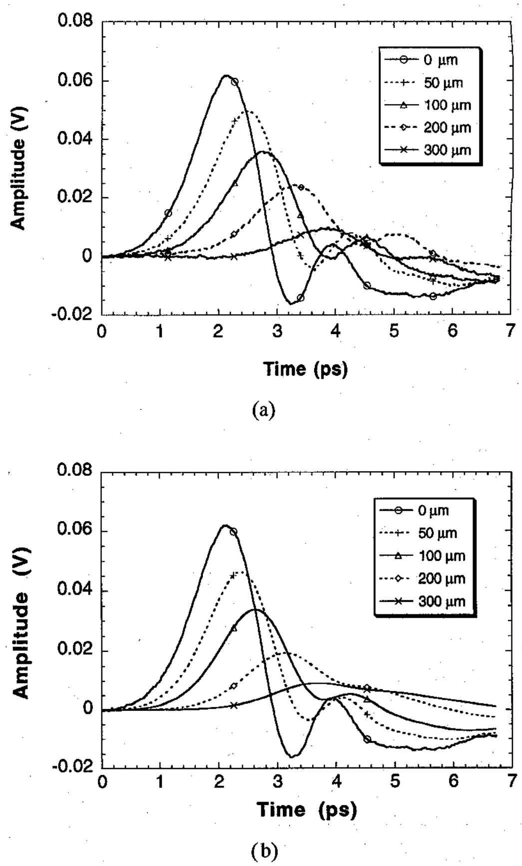

Fig. 3. Pulse propagation on coplanar stripline fabricated on 5-mho/cm GaAs substrate. (a) Experimental results probed by electro-optic sampling technique and (b) simulation results obtained by using the experimental input to the modeling code.

conductance of the layer (5 mho/cm), the width (20 μm), spacing (10 μm), thickness (3000 Å), and resistivity (2.4 $\times$ 10^{-8} ohm-m) of the gold electrodes, and the substrate thickness (500 μm). The values of g_1, g_2, and τ_m were calculated from the above input parameters in the program. The result is shown in Fig. 3(b), with good agreement with the experiment found. Although the doped layer of the experimental sample is only 2 μm thick, most of the electric field is still confined in this layer because the doped carriers screen the field to keep it from penetrating deeply into the semi-insulating GaAs layer. This is contrary to the undoped case, which has a field penetration depth on the order of the electrode spacing. However, small differences were still observed in the amplitude and phase. The difference in the absorption is believed to be due to the finite thickness of the conducting layer of our experimental sample. Therefore, some portion of the electric field of the propagating pulse was not experiencing the effect of the lossy layer, and the attenuation was smaller in the experiments than in the simulation. This was due to the fact that the latter assumed that all the electric field was confined in the infinite conducting substrate. The small difference in the velocity of the peak of the pulse propagating may arise since the model does not include the change of effective permittivity due to the carrier doping in (5).

B. Picosecond Pulse Propagation on a Modulation-Doped Layer

Another measurement was also made using a modulation-doped layer as a substrate for the CPS, since this layer is typically used in high-frequency transistors. The layer consisted of AlGaAs/GaAs MQW's, with a modulation doping of 2×10^{18} cm^{-3} as shown in Fig. 4. We have used MQW's because of the scaling problem cited in the previous section. Very high-speed MODFET's are typically made with a modulation-doped single-quantum-well (QW) layer, with the separation between the drain and source being shorter than 1 μm for a submicrometer-gate-length transistor. However, the separation of our transmission line in this experiment was limited to 10 μm due to switching considerations. Therefore, a smaller portion of the electric field would have entered the doped layer, and resulted in lower attenuation if the actual device with a single QW was used. The scaling was not completely accurate, but gave us a feeling for how much the electrical pulse would be attenuated under conditions similar to those experienced by actual devices, when a fast signal launched from one end of the gate propagates down its width. As can be seen from Fig. 5, the strong absorption appeared in the propagation after only 50 μm, which is a typical width for a MODFET gate. Fig. 6 shows the frequency-dependent attenuation calculated from the fast Fourier transforms of the waveforms. Remarkably, the attenuation had a linear frequency dependence up to 1 THz, in contrast to the cubic dependence under quasi-static approximations [27] or the quadratic dependence due to the radiation loss [11] of a coplanar transmission line on low-loss substrate. The reason was that most of the absorption came from the conductive loss due to the high-mobility free carriers, which was expected from our model when the substrate loss dominated.

IV. Summary

A propagation model for high-frequency electrical signal propagation on lossy semiconductor substrates has been developed using the extended distributed-circuit model with the inclusion of substrate loss through the loss tangent. The loss tangent included the effect of free carriers contributing to the attenuation and dispersion using the Drude model of conductivity. The validity of this model was also verified with picosecond electrical pulse propagation experiments. The modeling and experiment have shown that a lossy substrate affects both the attenuation and dispersion of the electrical pulse. Good agreement of the modeling with the experiment leads us to believe that the simple model can be used to quickly predict, to "first order," the degree of distortion to be expected from broad-bandwidth propagation on CPS fabricated on lossy substrates.

In addition, the pulse propagation on a modulation-doped multiple-quantum-well substrate has been studied experimentally. This investigation simulated high-frequency signal propagation along a MODFET gate and demonstrated a linear frequency dependence in the attenuation. This result implied that the modeling of a MODFET should include the loss of the input signal along the gate, especially when the gate is long. This attenuation factor should also be considered in the design of high-speed transistors such as MODFET's and MESFET's.

350 Å	GaAs	2×10^{18} cm^{-3}	ohmic contact
300 Å	$Al_{0.3}Ga_{0.7}As$	2×10^{18} cm^{-3}	
40 Å	$Al_{0.3}Ga_{0.7}As$	i	spacer
100 Å	GaAs	i	quantum well
40 Å	$Al_{0.3}Ga_{0.7}As$	i	spacer
120 Å	$Al_{0.3}Ga_{0.7}As$	2×10^{18} cm^{-3}	doped layer
40 repetitions of above 4 layers			
300 Å	$Al_{0.3}Ga_{0.7}As$	i	
1 μm	LT-GaAs	i	switch layer
3000 Å	GaAs	i	buffer
	SI GaAs		substrate

Fig. 4. Modulation-doped layer structure used as a substrate under the coplanar stripline.

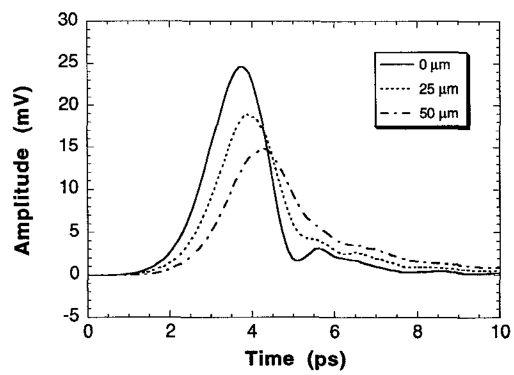

Fig. 5. Measured waveforms of the electrical pulses propagating on modulation-doped layer.

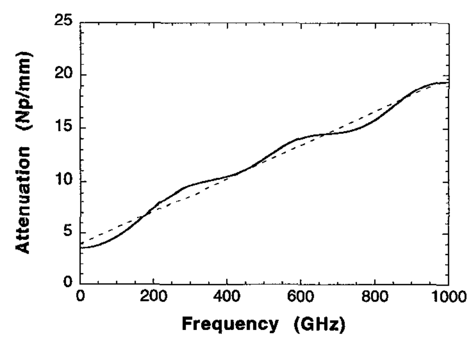

Fig. 6. Frequency-dependent attenuation of the coplanar stripline fabricated on a modulation-doped layer shown in Fig. 4. The attenuation is calculated from the fast Fourier transforms of the time-domain waveforms shown in Fig. 5. The dotted line is a linear fit to the experimental result.

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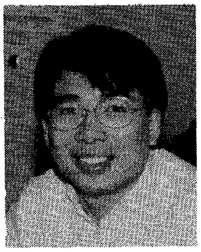

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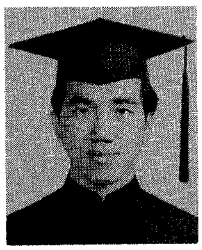
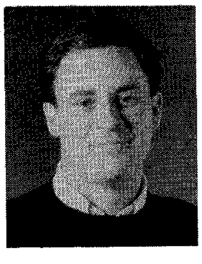
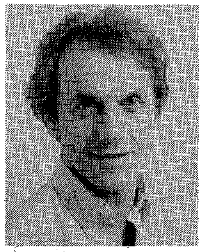


Hsi-Huai Wang (S'93) was born in Taichung, Taiwan on July 12, 1966. He received the B.S. degree in physics from the National Taiwan University, Taipei, Taiwan, in 1988 and received the M.S. degree in electrical engineering from the University of Michigan, Ann Arbor, in 1993. He is currently working towards the Ph.D. degree within the Center for Ultrafast Optical Science at the University of Michigan. His research involves high-speed optoelectronic material characterizations, cryogenic electro-optic sampling technique, and high-speed photodetectors.



John F. Whitaker (S'84–M'88) received the B.Sc. degree in physics from Bucknell University, Lewisburg, PA, in 1981, and the M.Sc. and Ph.D. degrees from the University of Rochester in Rochester, NY in 1983 and 1988, respectively. Upon completion of his dissertation he was awarded a Postdoctoral Fellowship at the Laboratory for Laser Energetics at the University of Rochester, working in picosecond optical electronics.

In 1989 he accepted a position as a Research Scientist in the Ultrafast Science Laboratory within the Department of Electrical Engineering and Computer Science at the University of Michigan in Ann Arbor. He is also currently the coordinator for the Ultrafast Technology area within the National Science Foundation Science and Technology Center for Ultrafast Optical Science. His research interests include the application of ultrahigh-temporal-response, optically based measurement systems for the investigation of the behavior of semiconductors, superconductors, dielectrics, transmission lines, devices, and circuits on picosecond and subpicosecond time scales.



Gerard A. Mourou (M'89) received the Ph.D. degree in physics from the University of Paris.

From 1978 to September 1988 he was at the University of Rochester where he held joint appointments as a professor at the Institute of Optics and as the Director for Ultrafast Science and Technology at the Laboratory for Laser Energetics. He is Director of the Ultrafast Science Laboratory, formed in 1988 within the Department of Electrical Engineering and Computer Science at the University of Michigan, Ann Arbor. He also holds a joint faculty appointment in Applied Physics. In 1991 he became Director of the Center for Ultrafast Optical Science, an NSF Science and Technology Center. Under his direct supervision is a research group of 45 scientists and engineers, approximately half are Ph.D. students. He has been a pioneer in the field of ultrafast photonics for nearly 20 years. He has published more than 150 papers and holds nine patents and six patent applications. He is a consultant to several private and governmental organizations, serves on the Scientific Board of the Laboratory for Optics of the Ecole Polytechnique-ENSTA and the Editorial Board of *Laser Focus,* and serves as a scientific advisor at the French Energy Atomic Commission.

Dr. Mourou was the initiator and co-chair of the conference on Picosecond Electronics and Optoelectronics, the first conference to bridge the fields of ultrafast optics and electronics. In 1992 he was awarded the Chevalier de l'ordre des Palmes Academiques.