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EXTERNAL ELECTRO-OPTIC INTEGRATED CIRCUIT PROBING*

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An external electro-optic measurement system with subpicosecond resolution has been developed. This electro-optic sampling system is designed to operate as a non-contact probe of voltages in electrical devices and circuits with modified wafer-level test equipment and no special circuit preparation. Measurements demonstrate the system's ability to probe continuous and pulsed signals on microwave integrated circuits on arbitrary substrates with single-micron spatial resolution. We also discuss the application of external electro-optic sampling to various aspects of time-domain circuit studies, including the generation of short electrical test pulses using novel photoconductive techniques and the propagation of pulses on interconnects.

1. INTRODUCTION

The characterization of both devices and circuits in the millimeter-wave range and beyond requires instrumentation possessing unprecedented resolution. The all-electronic network analyzer, relying upon physical contact for an electrical connection to a circuit under test, is essential to the determination of the rf and high-frequency properties of microwave components. However, this measurement technique has an operating frequency range which is limited to the millimeter-wave regime, and it is also somewhat deficient in terms of flexibility. Contacts to a circuit for measurement purposes, such as wire bonds or "Cascade-type" probes, not only may prove to be destructive to the circuit, but they also add the effects of their parasitic circuit parameters to the resulting data, and these effects must be de-embedded to find the actual circuit response. Furthermore, the bandwidth covered by any one set of test fixtures is limited, and in order to test over a broad spectrum at a wide variety of nodes in a monolithic microwave integrated circuit (MMIC), a substantial amount of time for each circuit is required. Thus, it is obvious that a much more flexible network analysis system for testing electrical devices and circuits operating in and above the millimeter-wave regime is required.

A technique for making extremely broadband measurements of electrical signals which currently exists involves the interaction of the disciplines of optics and electronics: electro-optic (e-o) sampling. [1] An external, non-contact, non-destructive, relatively non-invasive variation of this technique [2,3] can be used to make rapid measurements of electrical quantities, including the S-parameters of a circuit or device. This external e-o sampling technique closely approaches the ideal probe for integrated circuits: applicability to circuits fabricated on any substrate; high temporal resolution so that one measurement can cover all

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frequencies of interest; high spatial resolution for ease of testing small structures; no contact requirements so that probing of internal nodes may be accomplished; low perturbation of signals in the circuit; table-top, room temperature test environment; and compatibility with cryogenic test equipment. This probe, designed to operate at the wafer level with conventional wafer probing equipment and without any special circuit preparation, has been developed and demonstrated. The principle employed is the same as that used in another measurement technique, internal electro-optic probing, [4] except that neither an electro-optic substrate nor optical polishing of the substrate are required for external testing. External e-o sampling is described in Section 2. Its application to waveform measurements on integrated circuits is discussed in Section 3.1.

The usefulness of a wide-band characterization instrument, and thus the eventual usefulness of high-frequency electronic components in general, is dependent upon the quality of the input test signal utilized. While measurements can be performed using a single-frequency to excite a circuit, a pulse excitation provides a broad input spectrum so that the response of a circuit to many different frequencies may be determined all at once. The most common method of electrical pulse generation is the excitation of a voltage-biased photoconductive element in a planar transmission structure by a short-pulse laser. [5,6] An evaluation of photoconductive switches/test-signal generators and the transmission lines hosting them is easily accomplished through the use of electro-optic sampling. A new technique for producing well-behaved (*i.e.* accurately transformable using Fourier analysis), short-duration pulses that are measured using external e-o sampling is examined in Section 3.2. The planar structures upon which short pulses propagate are also of utmost importance to the operation of microwave integrated circuits, since the skin effect due to metal electrodes and dispersion mechanisms due to substrates and higher-order modes lead to the distortion of waveforms. An investigation into the loss mechanisms and the potential improvements of electrodes using external e-o sampling is reported in Section 3.3.

2. EXTERNAL ELECTRO-OPTIC CHARACTERIZATION

The external electro-optic probing technique employs an extremely small birefringent crystal as a proximity electric-field sensor, determining electric potential by measuring the strength of the fringing electric field. A schematic of the external e-o sampling system is shown in Fig. 1. The energy in a train of short pulses is divided so that two beams, excitation and sampling, are available. The excitation beam is used to generate carriers in a photoconductive switch, resulting in a voltage waveform that can be measured using e-o sampling. Alternatively, this trigger beam can be used to synchronize an rf synthesizer to the 100-MHz repetition rate of the laser so that the input to the component under test is a single frequency. The sampling beam is guided to the probe station using an optical fiber for flexibility, and it then passes through several optical components and a birefringent crystal, where its polarization is modulated by the electric field from a circuit via the interaction with the crystal (the Pockels effect). The compensator retards the phase of the polarization so that when no electrical signal is present on the Pockels cell, the output of the analyzer is 50% of the incident light. When this condition is achieved, the transmission function of the Pockels cell is linear with the applied electric field, or voltage, and the crystal is a linear intensity modulator. By varying an optical delay for the excitation beam, the sampling pulses have the opportunity to probe the amplitude at many points in a voltage waveform as it passes the modulator. The eyepiece is used to observe, along the axis of the sampling beam, the position of the probe tip with respect to the circuit electrodes

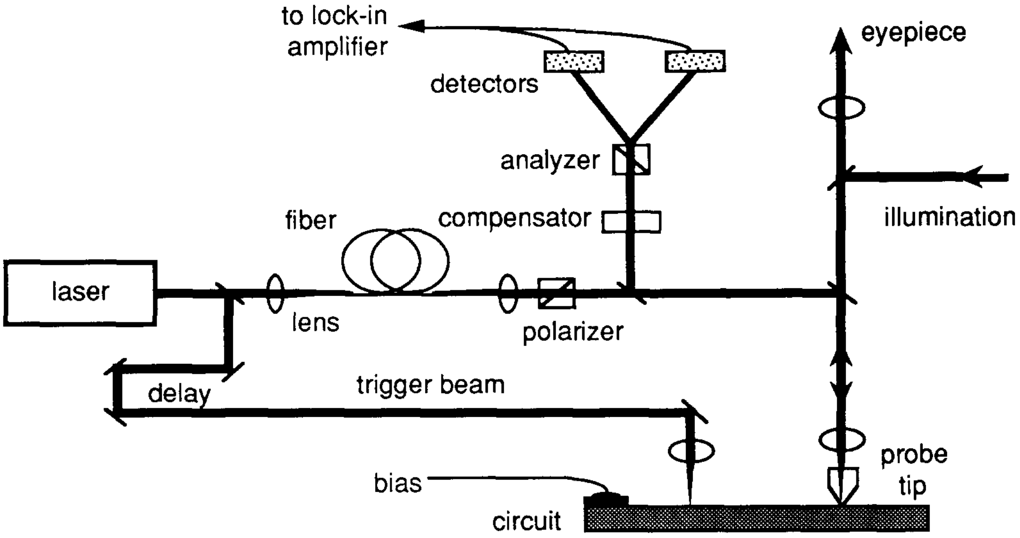

FIGURE 1
Schematic of the external electro-optic sampling system.

and the position of the sampling beam on the tip surface. The probe station, containing all of the optical components, is then translated so that the probe tip may be positioned to measure waveforms at any point in a circuit.

Since the optical probe beam may be focused down to a spot size less than 5 µm in diameter at the bottom of the crystal, good spatial resolution is achieved using this testing method. Additionally, no contact to the circuit is necessary, and thus no charge is removed. In this way, very brief electrical transients, with broad, continuous spectra, can be measured in order to determine the input to a microwave component, any reflection from the component, and the resulting output signal. Since the electro-optic medium is external to a circuit under test, this technique does not rely on any optical properties of the circuit substrate itself, and a wide variety of circuit embodiments may be tested.

The positions of the electro-optic probe beams for two *different* sampling configurations - transverse and longitudinal - are shown in Fig. 2(a). This figure schematically depicts the electric-field lines from a propagating waveform in a circuit and a beam of short laser pulses interacting in a birefringent crystal. The e-o probe tip, fabricated using different materials depending on which configuration is being used, is glued to a polished fused silica substrate with optical cement in order to provide support (the e-o crystal is only hundreds of microns high and tens of microns wide). The transverse e-o crystal, which would be made of lithium tantalate ($LiTaO_3$), is used to measure a fringing e-field perpendicular to the probe beam, while the longitudinal crystal, fabricated of deuterated potassium dihydrogen phosphate (KD*P) or bismuth silicate ($BiSO_3$), is used to measure field components that are parallel to the probe beam (perpendicular to the surface of the electrodes).

When a longitudinal tip is used, the most accurate measure of the potential of that electrode carrying the broadband waveform is obtained. Figure 2(b) indicates the

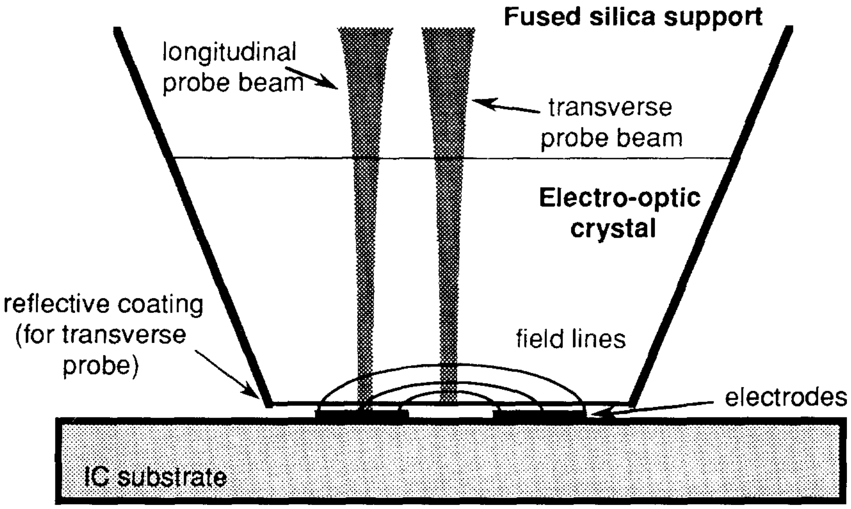

FIGURE 2(a)
The external electro-optic probe tip, showing two different modulator configurations, transverse and longitudinal. With a transverse electro-optic crystal, the optical beam direction is perpendicular to the electric field lines fringing above an integrated circuit. With a longitudinal crystal, the optical beam and electric field lines are parallel. The probe beams represent a train of short laser pulses used to time-resolve an electrical signal.

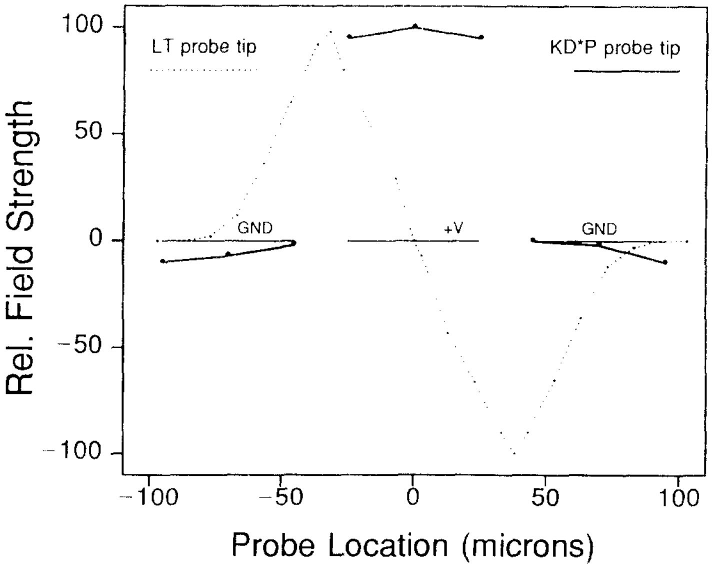

FIGURE 2(b)
Field strength - which may be translated to voltage - as measured versus position on a coplanar waveguide using external electro-optic sampling. The solid line indicates the field strength measured with the longitudinal KD*P crystal, while the dotted line indicates that measured using the transverse lithium tantalate crystal.

relative field strength measured over each of the electrodes of a coplanar waveguide using the two varieties of electro-optic probes. The longitudinal probe, which may be reflected off of an electrode rather than a high-reflectance coating as shown in Fig. 2(a), is seen in Fig. 2(b) to measure the e-field corresponding to +V only over the width of the center conductor. The transverse probe tip, however, is used to measure the field normal to the probe beam so that the same +V is only found over a small range of position directly between the electrodes. The longitudinal tip therefore is able to determine the voltage much more quickly and accurately by sensing the e-field over an arbitrary position of a line, while it is also immune to cross-talk fields from neighboring transmission structures.

The temporal resolution of this technique is fundamentally dictated by the duration of the probing optical pulse, since it acts as the sampling gate in the electro-optic sampling oscilloscope. In our case, measurements were made using 80-fs long pulses at a wavelength of 630 nm from a colliding-pulse mode-locked dye laser. However, the ultimate frequency response is determined by the first lattice resonance of the electro-optic crystal used as the modulator, which in general occurs in the terahertz regime. In the case of lithium tantalate, the crystal used for transverse electro-optic probing, this resonance occurs in excess of 6 THz, and this limits the time response of the probe to approximately 300 fs. The Fourier transform measurement bandwidth of this type of probe is thus somewhat greater than one terahertz.

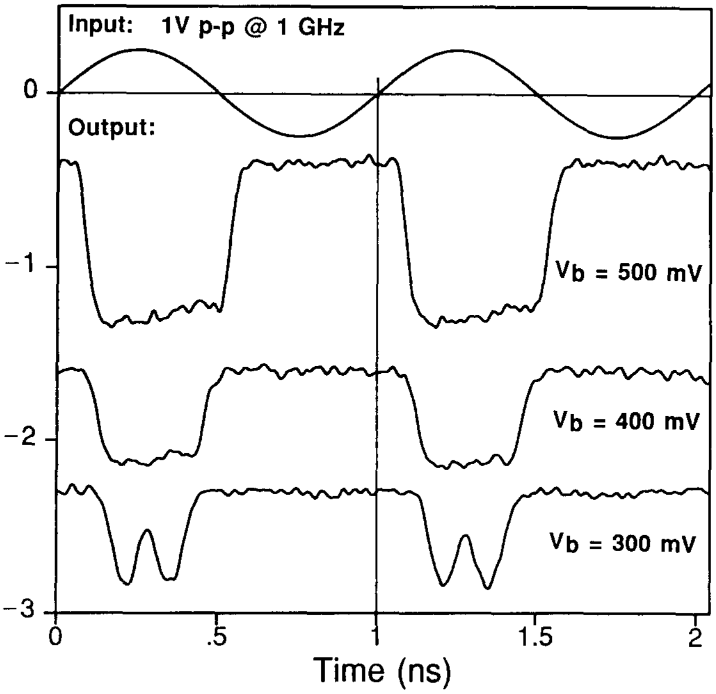

FIGURE 3
Output of the inverting input buffer of a GaAs selectively doped heterostructure transistor (SDHT) prescaler integrated circuit with a 1-GHz input signal.

3. APPLICATIONS OF EXTERNAL ELECTRO-OPTIC SAMPLING

3.1 Signal Characterization in Integrated Circuits

The external electro-optic testing technique has been applied to several integrated circuits in order to prove its utility. The first of these to be discussed is a digital circuit, a GaAs selectively-doped heterostructure transistor prescaler. In this case, waveforms on a transmission line with 4-μm features at the output of the input buffer of the circuit were measured using a transverse e-o probe. The buffer consisted of two banks of three inverter stages, each generating clock and complementary clock output signals. Each inverter consisted of two transistors, one for switching and one for an active load. Measurements were made at this internal node of the circuit on small lines in order to show that signals could be probed with excellent spatial resolution at points inaccessible to conventional "Cascade-type" probes. Figure 3 demonstrates the buffer output when a 1.0-GHz continuous signal is input to the circuit, and the dc bias is varied from above the switching threshold of the inverter chain (where V_{th} for each inverter is between 0.4 - 0.5 V) to below threshold.

Measurements were also made on several analog, narrow-band, millimeter-wave MMICs. In this case the signal to be measured was not a synthesized sinusoidal waveform, but rather it originated at the output of a photoconductive switch driven by the excitation beam. These step impulses were introduced to the first gate of a 0.4-μm-gate-length MESFET in either a Texas Instruments single or double stage 100-mW power amplifier MMIC. The output electrical signals were then measured above the 30-μm-wide microstrip transmission lines using a transverse e-o probe at the outputs of the amplifier stages. Figure 4 displays the Fourier transforms of the measured time-domain waveforms for three different drain voltages in the single stage MMIC. Similar waveforms were obtained at the outputs of the first and second stages of the two-stage amplifier, with the latter

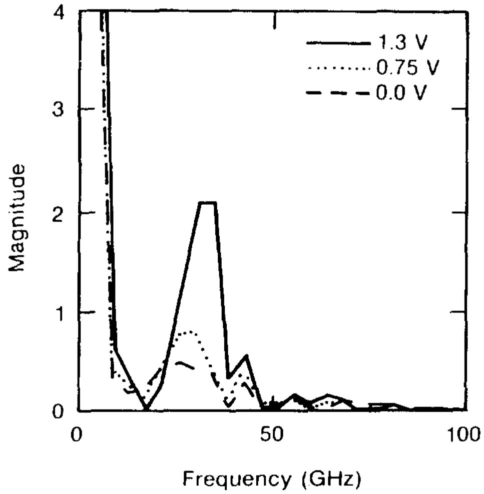

FIGURE 4
Spectra of waveforms sampled at the output of a narrow-band MESFET single-stage amplifier MMIC for three different values of drain bias (up to saturation).

exhibiting greater amplitude. An increase in the amplitude of the spectrum over a narrow band centered at 32.5 GHz was observed.

Measurements have also been made on several other circuits in order to illustrate non-contact, e-o sampling of signals in circuits having non-electro-optic substrate materials (such as GaAs, used in ref. 4.). A very clean 1.0-GHz clock waveform was measured with a transverse probe on-chip across a 4-μm space between an input clock line and an adjacent power supply line in a high-speed NMOS silicon 12-bit multiplexer. The clock signal was approximately 200-mV peak-to-peak, and it was generated by phase-locked microwave-driver circuitry and scanned at a 1-kHz rate. In this particular case, 100 scans were averaged in 400 ms and an excellent signal-to-noise ratio was obtained.

3.2 Ultrashort Pulses for Broadband Characterization

In order to be able to exploit the outstanding bandwidth in a pulse generated using a photoconductive switch, one must be able to accurately determine the Fourier transform of the time-domain signal. If the pulse is long so that many reflections may become superimposed on its trailing edge, the signal must be truncated in a manner that estimates the true shape of the waveform. This may cause an error in the computed spectrum. Furthermore, if the input to a circuit is to be distinguished from the resulting reflection, the input must be short enough or the transmission line long enough that the two signals can be resolved. Since a long transmission line may cause much distortion on its own, it is necessary to generate a short, Gaussian-shaped signal.

Semi-insulating GaAs has typically been used as a switch material, but since its recombination time is on the order of nanoseconds instead of picoseconds, step impulses only have been generated. Pulses have been created using photoconductive switching elements based on amorphous silicon [7] and either radiation-damaged or implanted InP [8] and silicon-on-sapphire. [9] These

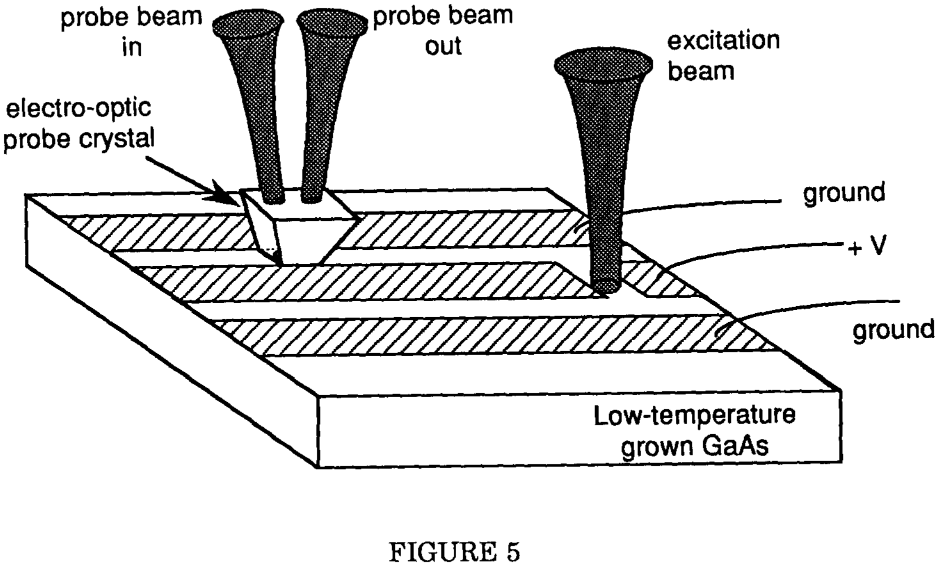

FIGURE 5
Coplanar waveguide transmission line fabricated on low-temperature-grown GaAs. The excitation beam generates a short electrical pulse and the probe beam samples the waveform as it passes the probe tip.

switches have all demonstrated subpicosecond response times. However, they have also proven to have serious shortcomings. Damaged materials that have rapid carrier recombination due to the traps that have been created tend to be unstable because the damage sites anneal away on a time scale of days or weeks. Silicon switches also have poor sensitivity due to the low mobility of the material. A process has now been devised at the MIT Lincoln Laboratory, however, to fabricate an ideal switch material by growing a micron-thick layer of GaAs via molecular-beam epitaxy (MBE) at a relatively low substrate temperature (200 °C). [10] This material exhibits a low dislocation density and thus a high mobility, it contains a high deep-level trap density that leads to a short photoexcited-carrier lifetime, and it has a greater resistivity and a higher dielectric breakdown than semi-insulating GaAs. In order to evaluate the materials potential merit as an outstanding test-signal generator, the e-o sampling system was used to test it.

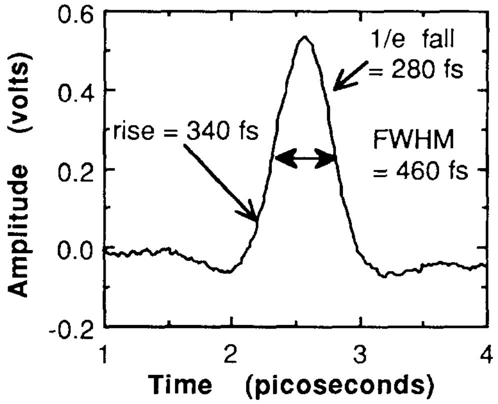

FIGURE 6(a)
Photoconductive response of low-temperature-grown GaAs switch.

A coplanar waveguide (CPW) transmission line was patterned on a sample of the low-temperature-grown (LT) GaAs. As indicated in Fig. 5, there was a gap placed in the center, positively biased electrode, which left exposed the LT GaAs as a switch gap. A transverse e-o probe tip was then positioned between the electrodes in order to measure the gap's response. The result, a Gaussian-like pulse with a full-width-at-half-maximum (FWHM) time of less than 500 fs, is shown in Fig. 6(a) as it was sampled several hundred microns after the switch. The spectrum of this pulse is given in Fig. 6(b), where it is seen that the relative energy in the signal is substantial up to 1.2 THz; after this point the spectrum became noisy. Pulses with amplitudes in excess of 4 V and FWHM less than 1 ps were also generated and detected using a 10-μm-long switch gap, a bias of 350 V, and a 50-pJ laser pulse.

3.3 Planar Circuit Interconnections

The dramatic frequency content of this short pulse can be used in order to study the behavior of circuits and devices over a broad band by making only several time-domain measurements. To date, these well-behaved signals have only been used to investigate the attenuation and phase velocity of a signal propagating on the coplanar waveguide. This is accomplished by simply translating the probe crystal in Fig. 5 to a greater distance from the switch and measuring the waveform.

Through this one additional measurement and its comparison to the original signal, the characteristics of the CPW were obtained from dc to 1.2 THz, as shown in Fig. 7. The attenuation follows the $f^{1/2}$ dependance of the skin effect, as well as a higher-order dependance due to surface-wave effects. The phase velocity, on the other hand, decreases with increasing frequency, again due to surface-wave-mode confinement in the higher permittivity material at high frequencies. This causes the higher frequencies represented by the rapid rising and falling edges of the pulse to travel more slowly than the lower frequencies, leading to an elongated rise time and oscillatory behavior on the trailing edge. [11]

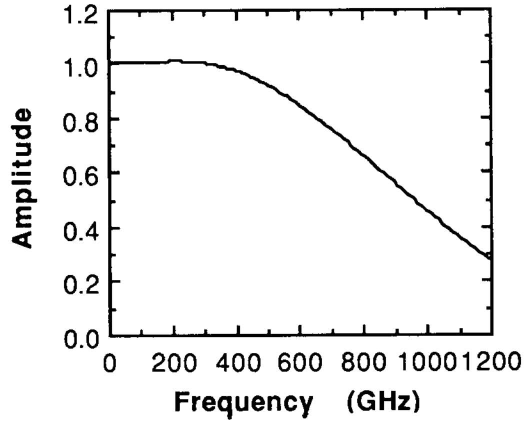

FIGURE 6(b)
Spectrum of pulse from Fig. 6(a).

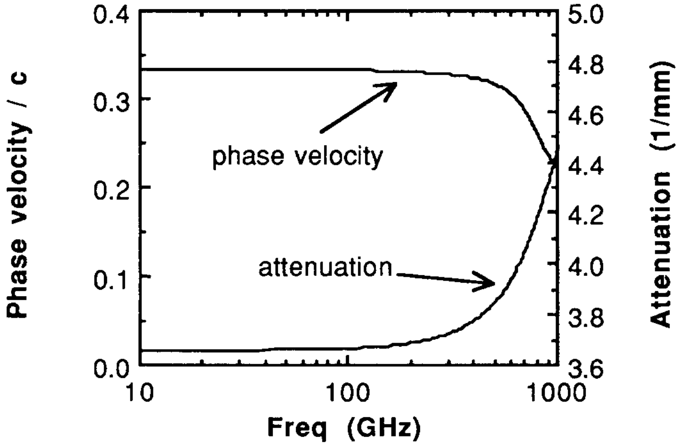

FIGURE 7
Attenuation and phase velocity of subpicosecond pulse due to coplanar waveguide, determined experimentally from two time-domain measurements.

While this modal dispersion distortion mechanism can be corrected to some extent by the use of smaller lines, skin-effect losses will always be present in normal metals. The use of superconductors as electrodes, however, leads to low-loss interconnects that preserve the amplitude of a propagating pulse. Niobium transmission lines, for instance, provide several orders of magnitude of attenuation less than copper electrodes up to the energy-gap frequency of the superconductor at a temperature roughly half of the Nb critical temperature. Extension of these superconducting properties to the new high-critical-temperature superconductors leads to the conclusion that ceramic lines may find applications as low-loss interconnects at temperatures of 77 K or even higher. This feature of superconducting lines has led to the development of a cryogenic external electro-optic sampling unit [12] which is being applied to the study of signal propagation on ordinary and high-temperature superconductors. [13,14] Figure 8 shows the first pulse measurement on a coplanar stripline of YBaCu-oxide compound as measured using a transverse e-o modulator. The temperature was approximately 2 K. The rise time of both the input and the output (overlayed on the input) after 5 mm of travel was 15 ps, and the deviation of the output was due to a reflection from the end of the line.

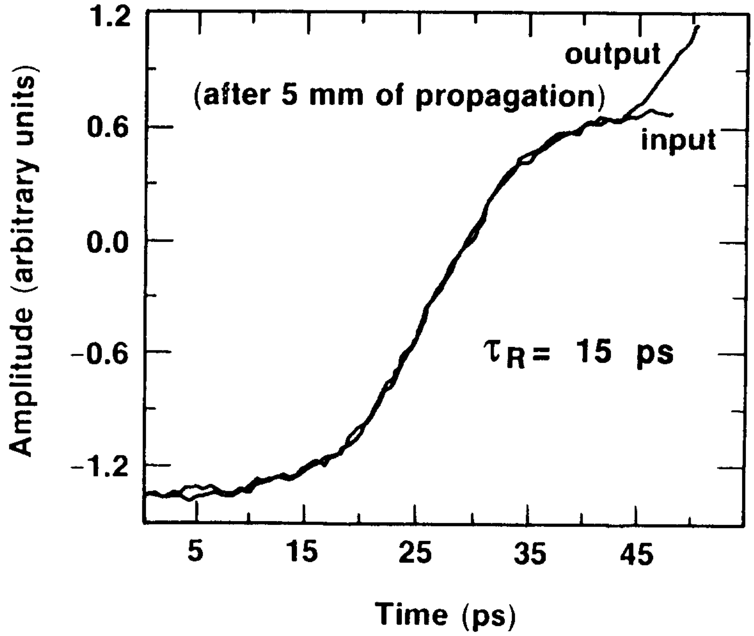

FIGURE 8
Propagation of short pulse on YBCO transmission line as measured with a transverse e-o probe in superfluid liquid helium.

4. CONCLUSION

We have demonstrated that the technique of external electro-optic sampling can be useful for probing microwave signals on integrated circuits fabricated on arbitrary substrates, having various open-boundary electrode configurations with few-micron dimensions. In addition, it has been shown that the electro-optic probe tip can measure voltage values on an integrated circuit chip, even in areas where physical contact made by a test instrument would be inappropriate.

Measurements with bandwidths in excess of 1 THz are seen to be within the capabilities of the electro-optic sampling technique, and they have been applied to the study of photoconductive switches and normal-metal and superconducting transmission structures. The high-temperature superconducting lines are now under intense scrutiny, and may provide very low-loss transmission within and between integrated ciruits of the future without the need for excessive cooling.

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