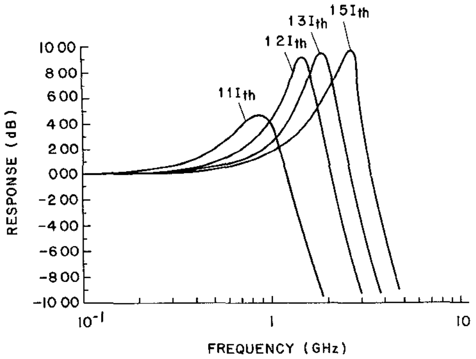

Fig. 3. Intrinsic laser frequency responses at different dc bias currents.

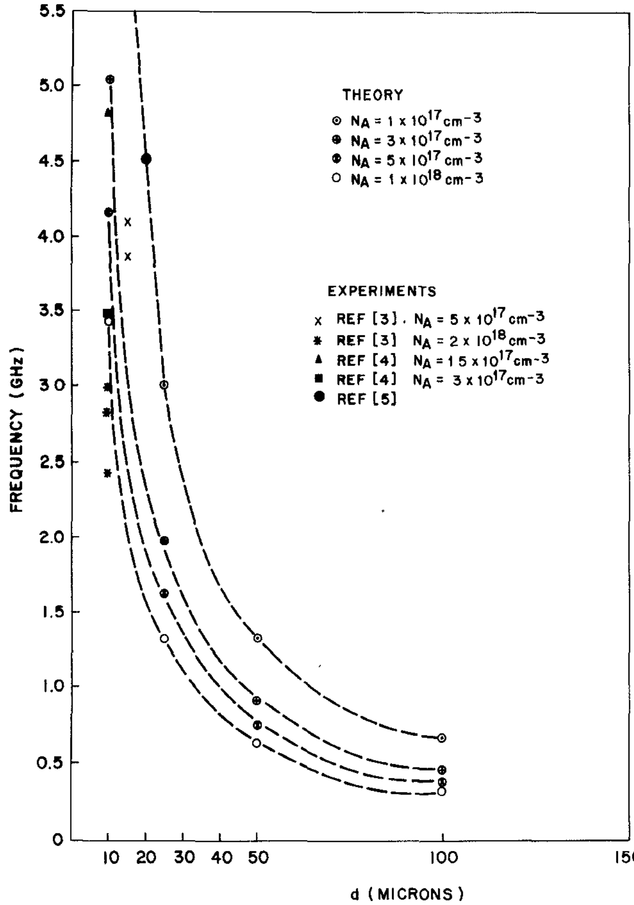

Fig. 4. Estimated 3 dB bandwidth of the overall network and some measured values.

pled into lasing mode $\beta = 0.5\times10^{-3}$; gain compression factor $\epsilon = 6.7\times10^{-24}$ m^2; active region volume $V = 7.2\times10^{-17}$ m^3; and laser threshold current $I_{th} = 14$ mA. A simple computer program has been developed to calculate the overall frequency response of the intrinsic laser and its parasitics. The estimated 3 dB bandwidth of the overall network as a function of the parameter d and for different values of N_A, together with some experimental values, are plotted in Fig. 4. It can be observed that the overall network cutoff frequencies (Fig. 4) are generally larger than those calculated for the laser parasitics themselves. This is due to the intrinsic laser resonant peak associated with relaxation oscillation (Fig. 3).

IV. Comments and Conclusions

A simple model for the DC-PBH laser parasitics and for the overall network frequency response was described in this paper and compared to certain measurements. It is shown that the blocking junction distributed capacitance can significantly degrade the frequency response of these lasers. The blocking junction half-width and the acceptor doping density reduction effects on the 3 dB modulation bandwidth increase are predicted. When the blocking junction half-width d is large ($d \sim 40$–100 μm) and for dc bias equal or greater than 30–50% above threshold, the intrinsic laser relaxation oscillation frequency is well above the laser parasitics cutoff frequency. Therefore, to improve the frequency response of the FP and DFB DC-PBH lasers, besides the optimization of the intrinsic laser parameters and the packaging parasitics, the blocking junction capacitance must be decreased.

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Design and Applications of Optically Controllable Finline Structures

K. UHDE AND R. EIMERTENBRINK

Abstract —**This paper describes the design of finline structures on a semiconducting substrate. Using high-resistivity silicon and gallium arsenide substrates, insertion losses between 1 dB and 2 dB have been achieved. By illuminating the slot region with a laser diode, attenuators and/or switches with on–off ratios up to −40 dB have been realized in the**

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26.5–40 GHz region. The attenuation, phase shift, and switching times are given. Further applications are also discussed.

I. Introduction

Within the last few years, there has been growing interest in the development of laser-controlled microwave devices. This is due to the advantages of optoelectronic devices, such as nearly perfect isolation between controlling and controlled signals, fast switching times, and the ability to handle high power, as well as to the increasing development of MMIC's.

The control of microwave signals by laser illumination is based on the photoconductivity effect. Changing the complex dielectric constant of a semiconducting substrate by an optically induced electron–hole plasma modifies the propagation constant of a passing microwave signal. Thus, an attenuation and/or phase shift can be achieved. Using these properties, several applications are possible [1]. Fast microwave switches [2]–[4] and phase shifters [5], [6] have been realized. Modulators [7] and sampling components [8] have been presented and the generation of short microwave pulses has been reported [4], [5], [9], [10]. Most of the devices are based on a stripline configuration in the lower frequency region or use a dielectric waveguide structure for applications in the millimeter-wave region at 94 GHz.

A structure which seems to be well suited for optoelectronic control is the finline structure. With its high field concentration in the slot region, it promises a high optoelectronic sensitivity. Then, high power sources such as Nd:YAG lasers can be replaced by laser diodes. In [11] and [12] we presented an optoelectronic switch in finline technique which works with CW and pulsed illumination. In the following, we wish to present detailed information. The requirements for achieving a small insertion loss with finlines on silicon and gallium arsenide substrates are discussed. In addition, experimental results are presented. Illuminating the slot region of a finline with a pulsed laser diode, the attenuation, phase shift, and switching times are given.

II. Design Requirements

In designing a microwave device on semiconducting substrate, the special properties of semiconductors have to be taken into account. Due to the high dielectric constant, a gradual transition between finline structure and empty waveguide is necessary. To avoid damage, a special device mounting with a grating structure has been used. As shown in [11], the insertion loss lies between 18 and 25 dB if a substrate material with small resistivity (in that case, 40–60 Ω·cm) is taken. Therefore, a material with high resistivity has been chosen. Most semiconductor wafers are available without metallization. Evaporating the metallization without substrate heating avoids additional doping as well as damage to the surface.

A. Transition Between Finline Structure and Metallic Waveguide

The transition between finline structure and waveguide can be divided into two parts. One is a section between a finline structure and a dielectric-filled waveguide, the other a section between a dielectric-filled and an empty waveguide. The first transition has been calculated according to [13]. This is a synthesis method. With a computer program, a prescribed input *VSWR* is converted to a slot contour. In the case of a thick substrate with high dielectric constant, the finline dispersion formula used is no longer exact. Introducing an additional term in the formula which defines the shunt susceptance jB_u reduces the deviation. Well-performing tapers have been achieved in this way. Designing the transition between dielectric-filled and empty waveguides,

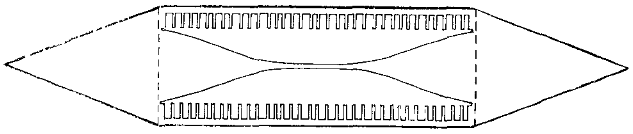

Fig. 1. Design of a finline structure on Si or GaAs substrate using a grating with variable width. The broken lines mark a structure with rectangular shape.

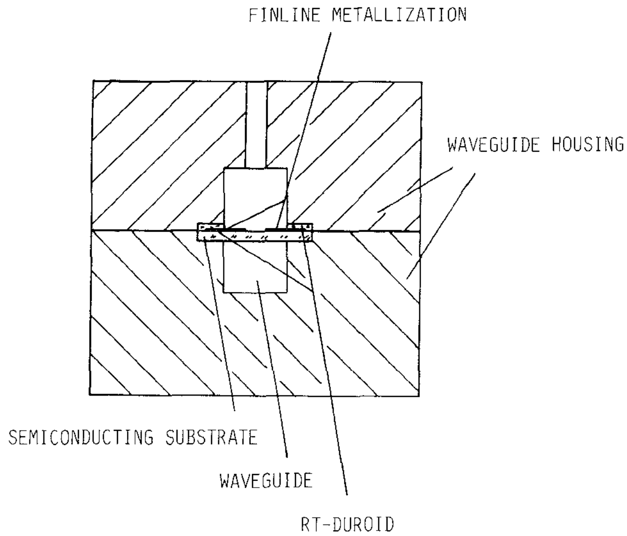

Fig. 2. Metallic waveguide housing.

a rectangular contour, as shown in Fig. 1 by broken lines, means a strong discontinuity. Small insertion loss has been measured if a silicon dioxide substrate is used [12]. Taking a finline on GaAs substrate, the insertion loss varies between 2 and 5 dB. In addition, large input reflections occur. Best results have been achieved with a symmetrically wedge shaped structure which is given in Fig. 1. Insertion losses between 1 and 2 dB have been obtained with finlines on Si and GaAs substrates [12].

B. Device Mounting

To fix the finline elastically in the waveguide, the configuration shown in Fig. 2 has been used. Between finline and metallic housing, there is a thin layer of flexible dielectric material (RT-Duroid). As the finline metallization is isolated from the metallic housing, a grating structure has been used to transform the open circuit at the end of the substrate into a short circuit at the waveguide walls. To avoid a large asymmetry, the dielectric constants of the RT-Duroid spacer ϵ_{rD} and of the semiconductor ϵ_{rS} should be similar. In addition, the thickness of the dielectric layer, d_D, is chosen to achieve similar capacitances per unit length between housing, dielectric, and semiconductor material, respectively. Hence

$$\frac{\epsilon_{rS}}{d_S} \approx \frac{\epsilon_{rD}}{d_D}.$$

In the above, d_S denotes the thickness of the semiconductor layer. Such a structure may be approximated by a triplate line, which is a TEM structure. Defining an effective dielectric constant, ϵ_{reff}, by

$$\epsilon_{reff} = \frac{1}{4}(d_D + d_S)\left(\frac{\epsilon_{rS}}{d_S} + \frac{\epsilon_{rD}}{d_D}\right)$$

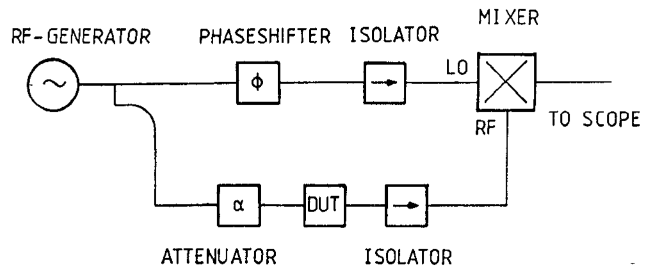

Fig. 3. Microwave bridge arrangement to measure the attenuation and phase shift in pulsed operation.

the length of the grating strips is given by

$$l \simeq \frac{\lambda}{4} = \frac{\lambda_0}{4\sqrt{\epsilon_{reff}}}$$

where λ_0 and λ are the wavelengths in free space and in the triplate line, respectively. To achieve broad-band operation, the characteristic impedances of the strips should be small. This leads to a large strip width. On the other hand, the strips should be longer than their width: $b \leqslant l/2$.

The complete grating structure can be designed by varying the width randomly (see Fig. 1). Then all strips show the same length but different widths. Another possibility is to use a constant width and, e.g., three different strip lengths (see [12]) which correspond to three frequencies: one in the center of the frequency band and the others at the band edges. In both cases, insertion losses between 1 and 2 dB have been achieved. Using the width variation which is a nonperiodic configuration, the insertion loss is smoother but on average the values are a little higher.

III. The Optical System

To realize a compact system, we have taken laser diodes instead of, say, Nd:YAG lasers. A laser diode (type LA65) has been chosen which works at a wavelength of 850 nm. It provides an optical power of 12 W ($I_D = 30$ A) in pulsed operation and is suitable for exciting Si and GaAs in a one-photon process. As the optical power is limited, a beam-focusing system has been inserted which consists of a microscope objective to broaden the laser beam and of a cylindrical lens to focus it on the slot region of a finline. To adjust the system, the laser diode is movable in both horizontal directions and the distance between the components can be varied. To avoid a reflection of the incident laser light, an optical coating may be advantageous. This can be achieved by a thin silicon dioxide layer. It has a thickness of a quarter wavelength of the incident light, thus acting as a quarter-wave transformator. Until now, such structures have not been measured.

IV. Microwave Properties

To measure attenuation and phase shift when the slot region of the finline is illuminated, a microwave bridge has been used. The measurement setup is shown in Fig. 3. A CW signal is divided with a directional coupler. One part of the signal is connected to the local oscillator input of a mixer via a phase shifter and an isolator. The phase of this reference signal can therefore be adjusted to achieve a maximum output signal. Reflections are avoided as well. The other path of the bridge is connected to the signal input of the mixer. It consists of a variable attenuator to calibrate the output signal, the device under test (DUT), which is the finline structure, and another isolator. The output pulse is displayed on an oscilloscope.

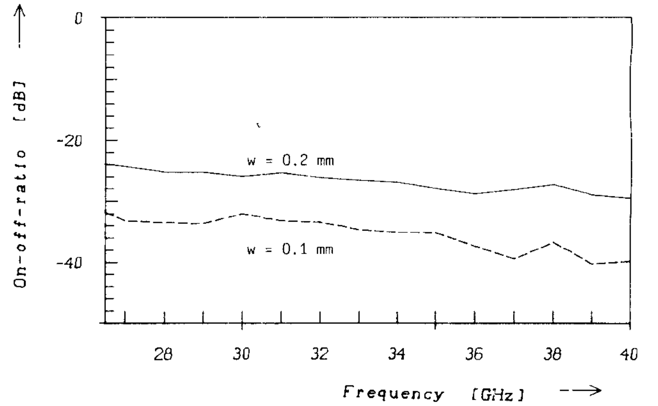

Fig. 4 Attenuation of a finline structure on high-resistivity Si substrate using two slot widths: $w = 0.1$ mm (solid line) and $w = 0.2$ mm (broken line)

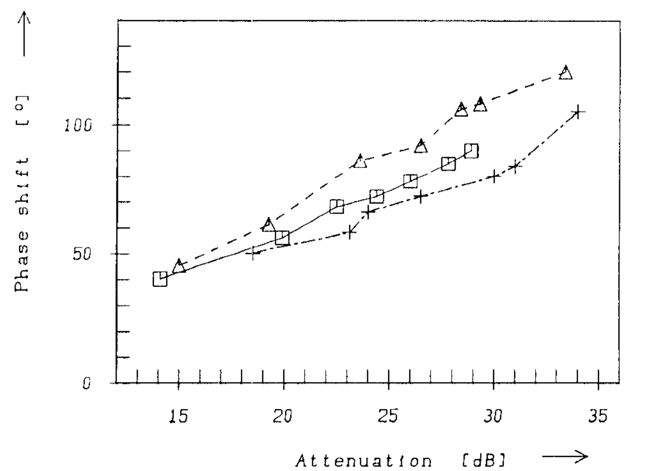

Fig. 5. Phase shift of a finline on high-resistivity Si substrate ($w = 0.1$ mm) versus attenuation at three frequencies $f = 27$ GHz (□), $f = 33$ GHz (△), and $f = 39$ GHz (+).

In the following, finline structures on both Si and GaAs substrates are investigated. Their metallization is evaporated. It consists of a thin layer of titanium (0.1 μm) and a second one of gold (0.3 μm). In Fig. 4, the attenuation of two finlines on Si substrate ($d_S = 0.38$ mm, $\rho = 2000$–4000 $\Omega \cdot$cm) with different slot widths is given versus frequency. The attenuation or on–off ratio is the ratio of the output signal with illumination to that without illumination. The on–off ratio lies between -24 and -30 dB if a finline with a slot width of 0.2 mm is used. Taking a structure with $w = 0.1$ mm, it is between -32 and -40 dB. A small decrease in on–off ratio versus frequency can be observed. Reducing the slot width increases the field concentration in the slot. Therefore, a larger attenuation has been obtained with a structure having a smaller slot width.

Varying the driving current of the pulsed laser diode changes the attenuation that can be achieved. In this way, corresponding values of phase shift and on–off ratio have been measured at three different frequencies (27, 33, 39 GHz). Fig. 5 presents the phase shift of a finline on Si substrate with a slot width of 0.1 mm versus attenuation at these frequencies. The phase shift increases with attenuation up to values of about 100°. With growing phase shift, the output signal diminishes to the lower mV region so that the measurement error increases with attenuation or phase shift.

Illuminating the slot region of a finline on GaAs substrate ($d_S = 0.45$ mm, $\rho = 10^6$ $\Omega \cdot$cm), the on–off ratio of finline struc-

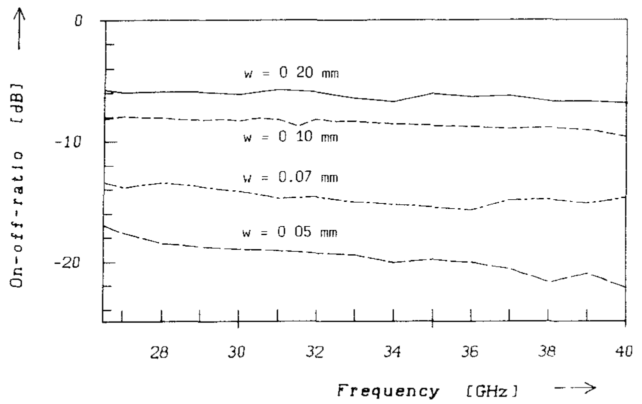

Fig. 6 Attenuation of a finline structure on intrinsic GaAs substrate using different slot widths: $w = 0.2$ mm (———), $w = 0.1$ mm (----), $w = 0.07$ mm (—-—), and $w = 0.05$ mm (—-—-).

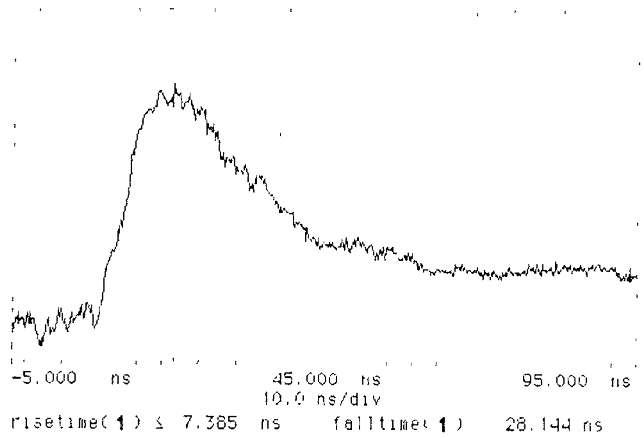

Fig. 7. Output voltage of the mixer in Fig 3 with balanced bridge, illuminating a finline on high-resistivity Si substrate ($w = 0.1$ mm)

tures with different slot widths has been measured versus frequency. Results are shown in Fig. 6. With a finline having a 0.2 mm slot width, the attenuation varies between -6 and -7 dB. Taking a structure with $w = 0.1$ mm, it lies between -8 and -10 dB. Reducing the slot width to 0.07 mm and 0.05 mm, on–off ratios up to -15 dB or -20 dB have been achieved, respectively. The obtained phase shift in GaAs is quite small.

The carrier lifetime in GaAs is about 100 ps. Only during this short time do the generated electron–hole pairs contribute to an attenuation. Therefore, smaller attenuations have been measured. The carrier lifetime in Si is in the μs region. This leads to a storage of the charge carriers, so that their number increases up to the end of the light pulse. In addition, there is a diffusion of charge carriers into the substrate material, which leads to a large phase shift. Due to the short carrier lifetime in GaAs, no phase shift has been detected.

Using an HP 54501A, the switching times have been investigated. The driving current of the laser diode ($I_{D\max} = 30$ A) has a rise time of 21 ns and a fall time of 46 ns. Taking a finline on Si substrate, an attenuation with a fall time of about 11 ns and a rise time of 8.8 μs has been achieved. With a halved current ($I_{D\max} = 15$ A) the fall time of attenuation is increased to 22 ns. Then a rise time of 3.9 μs has been measured. Since fewer charge carriers have been generated, it takes less time for them to recombine. Investigating a finline on GaAs substrate, the fall time (22 ns) and rise time (38 ns) of the attenuation are similar to the switching times of the bias current. Halving the current shows only small influence. As the maximum attenuation becomes less, the fall time decreases to about 16 ns, while the rise time is not changed.

V. Further Applications

To achieve short microwave pulses, a balanced microwave bridge has often been used. Then the microwave pulse is generated by changing the phase or amplitude of one of the signals. To investigate whether a finline can be used for such an application, the output voltage of the mixer in Fig. 3 has been measured. Without illumination it has been set to zero by adjusting the phase shifter. Illuminating the slot region of a finline on Si substrate, the pulse shown in Fig. 7 has been detected. The unit of the ordinate is 5 mV/div. This signal is influenced by both a phase shift and an attenuation. It has a short rise time ($\leqslant 7$ ns), which is caused by a rapidly increasing phase shift. After the attenuation reaches its maximum value, the output signal becomes very small. Replacing the mixer in the microwave bridge (Fig. 3) by a coupler, microwave pulses with short rise times can be realized. Due to the long carrier lifetime, the fall times will be long. As in [4] and [5], an additional switch-off pulse is necessary.

Illuminating the slot region of a finline on semiconducting substrate, a phase shift has been measured. It is, however, accompanied by strong attenuation. If only a part of the slot is illuminated, one can switch, say, between a finline with large and small slot width, which may lead to a large phase shift with smaller attenuation. To avoid carrier diffusion, it is, however, not sufficient to cover that part of the slot region which should not become conductive. A kind of diffusion barrier should also be inserted. This may be a trench which is etched into the semiconducting substrate and afterwards filled with an isolator, e.g. silicon dioxide. Avoiding abrupt transitions, a considerable phase shift with acceptable attenuation could be realized.

VI. Conclusion

The design of finline structures on semiconducting substrate has been discussed in detail. Structures on high-resistivity silicon and gallium arsenide substrate with an insertion loss between 1 and 2 dB have been presented. Illuminating the slot region by a pulsed laser diode, attenuations of up to -40 dB have been achieved if a beam-focusing system is used. A further improvement can be obtained by an optical coating of the substrate. Due to carrier diffusion in Si, a large phase shift has been detected. The switching properties have been investigated, and switching times in the nanosecond region have been measured. They approach the rise and fall times of the driving current of the laser diode. To decrease the switching times, a faster light source or a driving circuit should be used. As there are no additional limitations, finline structures are probably suitable for picosecond applications. Finally, the generation of short microwave pulses with finlines and a phase shifter in finline technique have been discussed.

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Picosecond Optoelectronic Measurement of *S* Parameters and Optical Response of an AlGaAs/GaAs HBT

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***Abstract*—The *S* parameters of an AlGaAs/GaAs heterojunction bipolar transistor (HBT) were measured using a picosecond optoelectronic system. The measured *S* parameters show qualitatively good agreement with those obtained using a conventional vector network analyzer. The optical response of the HBT was also measured using this system by directly illuminating the base–collector region. Used as a phototransistor, the HBT showed pulse widths with FWHM as short as 15 ps.**

I. INTRODUCTION

In recent years there has been steady progress in the development of high-frequency semiconductor devices and millimeter-wave integrated circuits. Present high-frequency transistors have cutoff frequencies well beyond the bandwidth that can be measured conveniently using conventional network analyzers. As a result, the millimeter-wave *S* parameters of devices are commonly calculated from the extrapolation of small-signal models of the transistor based on the microwave measurements. This extrapolation method has not been proven to be reliable in predicting the behavior of devices at frequencies much higher than the measured frequency. By using external mixers the present bandwidth of network analyzers has been extended to about 110 GHz. But several difficulties arise in characterizing devices in the millimeter-wave region. At high frequencies the transistors have to be mounted in test fixtures with waveguide-to-microstrip transitions. It is difficult to design wide-bandwidth and low-loss waveguide-to-microstrip transitions. The actual *S* parameters of the device have to be de-embedded from the test fixture, and with transitions having a high insertion loss erroneous results can be obtained.

Use of time-domain techniques for characterization of devices offers advantages over the frequency-domain techniques used by most network analyzers. By measuring the response of the device in the time domain and taking the Fourier transform of the data, the frequency performance of the device can be calculated. The response of the device can be "windowed" in the time domain and separated from reflections due to transitions and other unwanted signals before it is analyzed. This will simplify de-embedding of the *S* parameters of devices. But the use of time-domain techniques for device characterization has been very limited due to a lack of availability of fast electrical pulse generators and oscilloscopes.

In order to improve and optimize the performance of millimeter-wave transistors it is important to have a simple technique for direct characterization of devices at very high frequencies. Picosecond optoelectronic techniques offer a new method for generating and sampling ultrafast electrical pulses [1]–[3]. These electrical pulses can be used to test the response of high-speed semiconductor devices [4] and integrated circuits [5], [6]. Using photoconductive switches, picosecond electrical pulses can be generated and sampled at a very short distance from a device. Therefore, the high-frequency signals do not have to travel through long sections of transmission lines and waveguide transitions, making this technique superior to conventional network analyzers. In this study, *S* parameters and the optical response of AlGaAs/GaAs heterojunction bipolar transistors (HBT's), which are very promising devices for applications in microwave and millimeter-wave integrated circuits [7], were characterized using picosecond optoelectronic techniques.

II. MEASUREMENT

An AlGaAs/GaAs HBT was mounted in an optoelectronic test fixture of the type shown in Fig. 1. The HBT tested had $3\times10\ \mu m^2$ emitter and self-aligned base ohmic metal. The structure and fabrication of this device were previously reported in detail [8]. The microstrip lines were fabricated using gold on silicon-on-sapphire (SOS) substrates. A thin layer of chromium was used to improve adhesion between the gold and the silicon surface. The sapphire substrates were about 125 μm thick and the microstrip lines were designed to have a 50 Ω impedance. The silicon epi-layer was about 0.5 μm thick and was heavily implanted with four different energies of silicon ions to shorten the carrier lifetime to subpicosecond levels [9].

On each side of the device there are two photoconductive switches, which consist of 25 μm gaps in the side microstrip lines. By applying a dc bias to a photoconductive switch and focusing a

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