A New Type of Optoelectronic Millimeter-Wave Finline Switches

Deming Xu, *Senior Member, IEEE*, Lie-pu Song, and Ke-qin Wu

***Abstract*—A new type of millimeter-wave finline switches constructed on teflon substrates is proposed, which can be easily fabricated and mounted. The experimental results are reported, which show less than 2 dB insertion loss in the region of 26–40 GHz and 23.4 dB on/off ratio have been reached. Because of its good compatibility with the conventional finline structures, it will have a wide application field. A very simple method has been given to analyze its behaviors which has successfully predicted the experimental results. A nonlinear relation between the photoconductivity and the light power is given which has been confirmed by experiment.**

I. Introduction

THERE HAS been continued and increasing interest over the past few years in the optical control of microwave and millimeter-wave devices and circuits. Such control is based on the photoconductive effect of semiconductors. These controls offer many attractive advantages [1]. Several optically controlled devices have been realized: switches, phase shifters, and modulators, which were based on either a stripline, or coplanar waveguide, or dielectric waveguide [2].

Research on optically controllable finline structures is an interesting topic, for the optoelectronic finline switch has shown a high optoelectronic sensitivity and, as well known, conventional finlines are important structures in the millimeter-wave region, especially for hybrid integrated circuits. This switch was first investigated by Platte *et al.* In their experiment, the insertion loss was about 6 dB, and on/off ratio, around 4 dB [3]. Uhde *et al.* have made considerable improvement for this switch, and demonstrated that the insertion loss between 1 and 2 dB and on/off ratio up to 40 dB had been achieved [4].

Both Platte and Uhde constructed the finlines on the semiconductor wafers. Because these materials are brittle, great care has to be taken in fabricating and mounting these finlines. Moreover, a low insertion loss of these finlines is more difficult to be realized because, in general, the loss and dielectric constant of semiconductors are higher than those of dielectric. It may be necessary to construct the optoelectronic finlines on semiconductor substrates for the monolithic integrated circuits. However, in the hybrid integrated circuits, it is easier to use dielectric substrates, since the difficulties mentioned above and the dimensional limitation of the semiconductor substrates can be avoided. In addition, the application field of the optoelectronic finline switches on a dielectric substrate may be widened owing to its good compatibility with the conventional finlines devices and circuits. In this paper, a new optoelectronic millimeter-wave switch, using a finline on a teflon substrate, is proposed.

In Section II, a nonlinear relation between the photoconductivity and light power will be given, and a simplified circuit model will be used to calculate the power transmission and reflection coefficients changing with the optical power. A method for measuring the power transmission and reflection simultaneously will be described in Section III. In Section IV, we will see that it is necessary to consider the nonlinearity between the optical power and the laser induced electron-hole plasma density which has rarely been mentioned in the papers on the optical control of microwave devices.

II. Configurations and Model

A. Configuration of the Device

The finlines were fabricated by the ordinary finline technique on teflon substrates, as shown in Fig. 1. The finline tapers were designed by the taper synthesis method [5]. A piece of semiconductor sheet, such as Si, GaAs, of InP, was stamped at the center of the finline. It is important to choose an appropriate shape and thickness for a certain type of semiconductor patches, so that a lower insertion loss and higher on/off ratio can be obtained.

B. Photoconductivity of the Semiconductors

When a laser beam illuminates a n-type semiconductor with high resistivity, and if $h\nu \geq Eg$, it will create an electron-hole plasma in the semiconductor. The dark conductivity

$$\sigma_o = |e|\,(n_o \mu_n + p_o \mu_p) \tag{1}$$

is thus increased by an amount as

$$\Delta r = |e|\,(\mu_n \Delta n + \mu_p \Delta p) \tag{2}$$

where e is the elementary charge; n_o, p_o are carrier concentration of the material; and Δn is the photo-induced plasma density. The photoexcited rate f, which is propor-

Manuscript received July 10, 1992; revised July 30, 1992. This project is supported by the National Nature Science Foundation of China.

The authors are with Shanghai University of Science and Technology, Shanghai 201800 China.

IEEE Log Number 9203710.

0018-9480/92$03.00 © 1992 IEEE

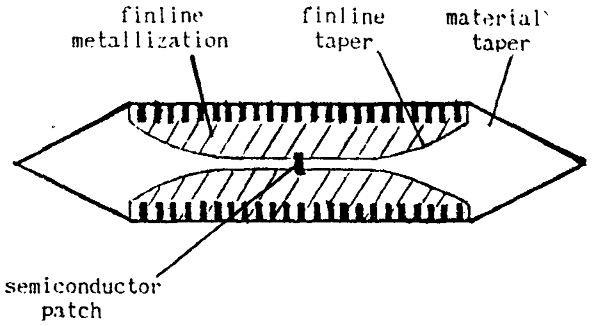


Fig. 1. Finline-on-teflon substrate with a semiconductor patch.

tional to the light power P, related with the photo-induced plasma as

$$f = c_1(n_o P_o + n_o \Delta n + p_o \Delta n + \Delta n^2) \tag{3}$$

In our case, $n_o \doteq 10^{12}\ \text{cm}^{-3} >> p_o$, so

$$P \doteq c_2(n_o \Delta n + \Delta n^2) \tag{4}$$

where c_1 and c_2 are ratio constants [6].

From (4) we can see that when $\Delta n \geq n_o$, (many optical controls of microwaves are in this case) the relation between the light power and the laser-induced plasma density is nonlinear. The nonlinear relation will be used in modelling the equivalent circuit (Section II-C), and be confirmed by experiment (Section III).

C. *The Equivalent Circuit for the Device*

The patch introduces discontinuities in the finline. As the finline is a non-TEM transmission line, accurate analysis will be very complicated, though it is possible to carry out by full wave analysis. Considering that the dimension of the patch is much smaller than the wavelength of the finline, here we use an equivalent circuit, somewhat similar to the p-i-n switch model, to describe the finline device as shown in Fig. 2. The $G(r)$ is a photoconductor, and the Cp is used to describe the capacitor effect between the metallization and the patch isolated by the glue and other parasitic effect.

We introduced a reduced light power r,

$$r = P/Po. \tag{5}$$

For a given P i.e., r, $G(r)$ can be determined by (1), (2), and (4), since

$$G(r) = c|e|\,\mu_n(n_o + \Delta n) \tag{6}$$

where c is a constant depending on the patch dimension.

The characteristic admittance of the finline at the center is Y_o. For simplifying the problem, the finline taper is regarded as an ideal matching transition, its small attenuation and mismatch have been neglected. The validity of the simple model has been proved by experiment which will be discussed below.

From the equivalent circuit shown in Fig. 2, the power reflection and transmission coefficients (Γ_p and T_p) and the insertion loss (L_p) can be obtained as [7]:

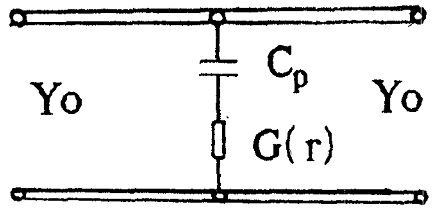


Fig. 2. Equivalent circuit of the optoelectronic finline.

$$\Gamma_p = |S_{11}|^2 = \frac{a^2 + x^2}{4 + a^2 + 4x + x^2} \tag{7}$$

$$T_p = |S_{21}|^2 = \frac{4}{4 + a^2 + 4x + x^2} \tag{8}$$

$$L_p = 1 - \Gamma_p - T_p \tag{9}$$

where

$$a = \frac{\omega C_p}{Y_o}\left(1 - \frac{1}{1 + \left(\frac{G(\gamma)}{\omega C_p}\right)^2}\right) \tag{10}$$

and

$$x = \frac{G(r)}{Y_o}\left(\frac{1}{1 + \left(\frac{G(r)}{\omega C_p}\right)^2}\right). \tag{11}$$

III. Measurement

The microwave bridge arrangement had been applied to measure the attenuation or phase shift of the optoelectronic finlines in pulse operation by Uhde *et al.* Our experimental set-up is shown in Fig. 3. The advantage of this set-up is that it can be used to measure the microwave power transmission and the reflection simultaneously, both of which are interesting to us.

The millimeter-wave source was an 80 mW solid-state source operating at 35.9 GHz. The optical illumination was derived from a mode-locked Nd:YAG laser. The pulse width of the 1.06 μm laser pulses was about 300 ns. Att. 1 was a variable attenuator used to choose a proper microwave power level, while Att. 2 was a standard attenuator. Prior to laser illumination, the microwave power could transmit through the DUT (the finline) with a little loss and the output of D1 or D2 was a horizontal line as the L in Fig. 4(a) or in 4(b), respectively. As the laser pulse struck the patch in DUT, the laser induced plasma causes reflection and loss in the finline. The waveform of D1 and D2 are shown in Fig. 4. After recording these waveforms and we read AF1 and AI1 from the Att. 2 by adjusting it so that the output of D1 reached the top level or the bottom level of the recorded waveform. AF2 and AI2 for D2 were obtained in a similar way.

To simplify the description, the microwave components used in the experiment were regarded as ideal, so

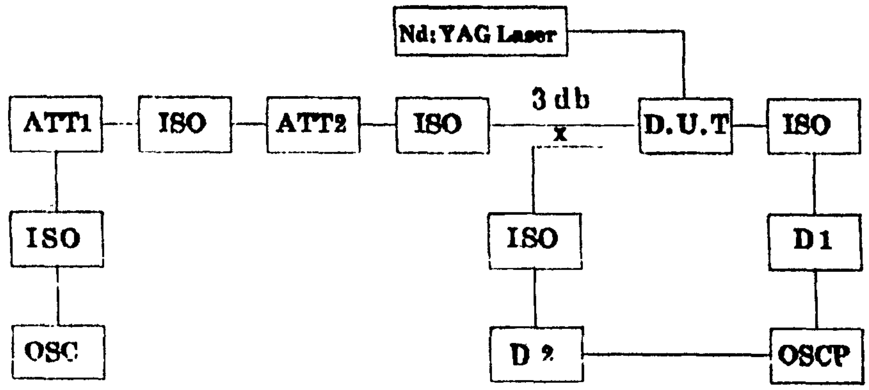
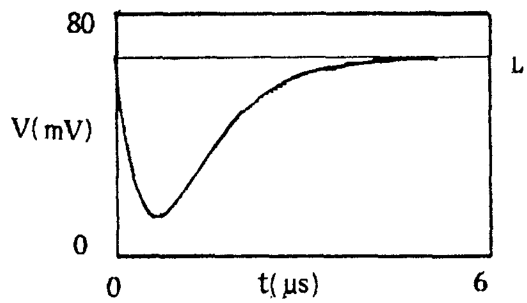
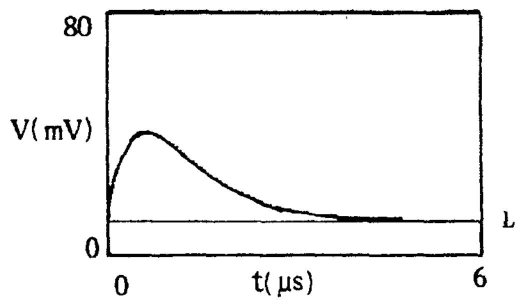


Fig. 3. Experiment set-up.



(a)



(b)

Fig. 4. (a) Transmission power waveform from detector D1. (b) Reflection power waveform from detector D2.

the incident power, transmission power and reflection power could be expressed as follows in dB.

$$Pi(dB) = PO - AI1 \tag{12}$$

$$Pt(dB) = PO - AF1 \tag{13}$$

$$Pr(dB) = 3 + 10\, lg\left[10\left(\frac{P_o - AI2}{10}\right) - 10\left(\frac{P_o - AF2}{10}\right)\right] \tag{14}$$

and, the power reflection and transmission coefficients could be obtained from

$$\Gamma p\,(dB) = Pr - Pi \tag{15}$$

$$Tp(dB) = Pt - Pi. \tag{16}$$

IV. Results and Discussion

Fig. 5 shows the measured insertion losses of the finline switch with no optical illumination. From which it can be seen that the insertion losses are less than 2 dB in the 30–38 GHz range. At 35.9 GHz, it is about 1.6 dB and at some frequency point, such as 29.5 GHz, it reaches near 1 dB. Lower insertion losses are expected for a better fabrication technology.

The experimental and calculated results of the microwave power reflection and transmission coefficients and the loss in the semiconductor for the optoelectronic finline versus the light power are shown in Fig. 6. The losses of the finline without patch are about 1 dB. The calculated curves would agree with the experimental results better if the small losses of the finline tapers are taken into account. The mismatch of the input taper might be the main cause of the variance between the calculated and experi-

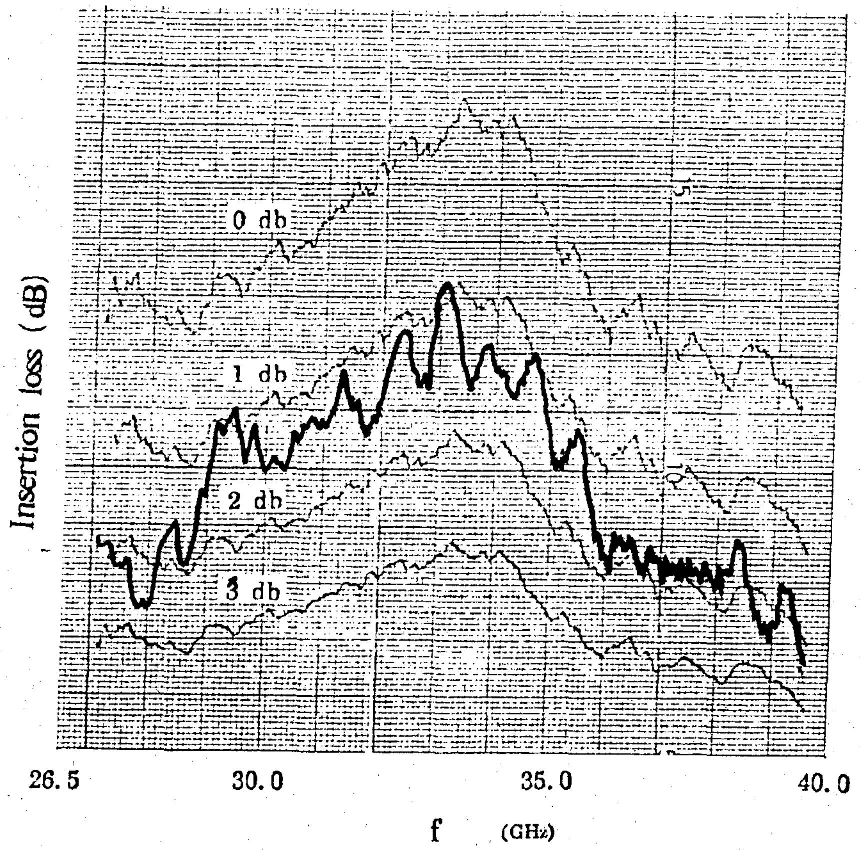


Fig. 5. Measured insertion loss of the finline with a Si patch, no optical illumination. The curves (the based lines, 0, 1, 2, 3 dB respectively) are used for calibration, which obtained by changeing the standard attenuator ATT2 value [8].

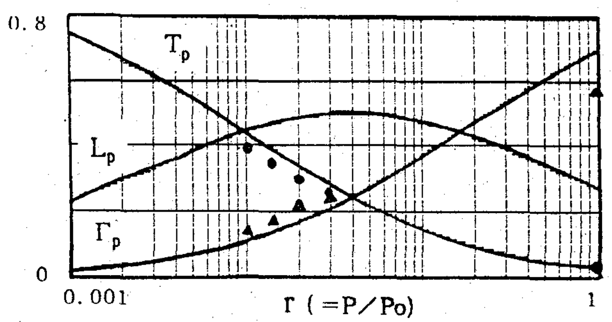


Fig. 6. Theoretical (the curves) and measured (the dots and trigons) results of the power reflection coefficients (Γ_p curve), the power transmission coefficients (T_p curve), and losses ($L_p = 1 - T_p - \Gamma_p$) in the optoelectronic finline switch versus the optical power (r).

mental results of the power reflection coefficients when they are large. Since no such curves have been given previously, these curves may be valuable for reference to design of different optically controllable finline components for various purposes.

V. Conclusions

A new type of optoelectronic finline switches has been proposed, of which 23.4 dB on/off ratio has been obtained. Its insertion losses in the region of 26–40 GHz were no more than 2 dB and are expected lower for a better technology. When two or more semiconductor patches are stamped on a finline with an optimum distance separations, a higher on/off ratio will be obtainable. From the experimental results shown in Fig. 6, we can see that the new structure may be used as an optically controllable attenuator. It is very important that the new configuration has good compatibility with the conventional finline, which is an important structure for hybrid integrated millimeter-wave circuits. Because the technology for the finlines on dielectric substrates is nearing its maturity, its applications are extensive, and different types of semiconductors may be applied in the new switches. The application field of the new switches is expected to be wide. From the viewpoint of practical usage, further investigations should be performed and are being carried out in our lab.

Since the equivalent circuit presented in this paper is very simple and has successfully predicted the experimental results, it will be useful for engineering. The nonlinear relation between the light power and photo-induced plasma, which is obvious from (4), has been confirmed by the experiments (Fig. 6). We believe that it is necessary to consider this nonlinearity in most of the microwave control devices with optical signals.

Acknowledgment

The authors wish to thank Mr. Chen Tao-lue and Lee Xin-wan and Prof. Lin Zhu-jie and Zhi Ting-ting for their valuable help.

REFERENCES

[1] C. H. Lee, "Picosecond optics and microwave technology," *IEEE Trans. Microwave Theory Tech.*, vol. 38, pp. 596–607, 1990.
[2] P. Cheung, D. P. Neikirk, and T. Itoh, "Optically controlled coplanar waveguide phase shifters," *IEEE Trans. Microwave Theory Tech.*, vol. 38, pp. 586–596, 1990.
[3] W. Platte, R. Glockler, and H. Brand, "GaAs-loaded metal waveguide components for high-speed low-VSWR optoelectronic millimeter-wave switching," *Electron Lett.*, vol. 20, pp. 608–610, 1984.
[4] K. Uhde and R. Eimertenbrink, "Design and applications of optically controllable finline structures," *IEEE Trans. Microwave Theory Tech.*, vol. 38, pp. 679÷683, 1990.
[5] C. Schieblich, J. K. Piotrowski, and J. H. Hinken, "Synthesis of optimum finline tapers using dispersion formulas for arbitrary slot widths and locations," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-32, pp. 1638–1655, 1984.
[6] K. Seeger, "Semiconductor Physics An Introduction," 3rd ed. New York: Springer-Verlag, 1985, pp. 386–392.
[7] K. C. Gupta *et al.*, "Computer-aided design of microwave circuits." Norwood, MA: Artech House, 1981, pp. 39.
[8] "High-frequency swept measurements," HP Application Note 183, Nov., 1975.

Deming Xu was born in Zhe-Jiang Province, China, in December 1934. He graduated from the Department of Physics, East China Normal University, Shanghai, China, in 1959. From 1959 to 1962 he was a graduate student in microwave theory and techniques at the same university. From 1982 to 1986 he was an Associate Professor.

Since 1986 he has been a Professor in Shanghai University of Science and Technology, Shanghai. His research interests currently focus on microwave and millimeter-wave techniques, nonelectric quantity testing, dielectric measurement, and microwave-optical interactions.

Mr. Xu is chairman of the China Society of Nonelectrical Quantities Testing, and vice-chairman of the Shanghai Society of Microwaves.

Lei-pu Song was born in Shanghai, PRC, on Feb. 1958. He received the B.S. and the M.S. degrees in electrical engineering from Shanghai Univ. of Science and Technology (SUST), Shanghai, in 1982 and 1990, respectively.

From 1982 to 1987 he worked with optical fiber components, etc. in the Wave Laboratory of SUST. His current interest is in the interaction between microwave and optical techniques, though his recent research has been in the optical control of microwave devices.

Ke-qin Wu was born in Shanghai, China, in 1943. He graduated from Department of Physics, Shanghai University of Science and Technology (SUST) in 1965.

Since then he has worked continuously in the Physics Department of SUST, where he was engaged in teaching Semiconductor Device Physics. He is currently an Associate Professor of SUST and has performed research on semiconductor devices and microwave integrated circuits. His current research interests include semiconductor device physics, high-speed optical electronics and optically controlled microwave devices.

Mr. Wu is a member of the Chinese Institute of Electronic (CIE).