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COMPRESSION AND RESHAPING OF PICOSECOND ELECTRICAL PULSES USING DISPERSIVE MICROWAVE TRANSMISSION LINES

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ABSTRACT

In this paper we newly propose a simple and effective method for reshaping and compressing picosecond electrical pulses generated from photoconductive switches. A piece of dispersive strip transmission line can be used as a "phase equalizer" to compensate the phase distortion included in asymmetric electrical pulses, resulting in effective reshaping and compression of these ultrashort pulses. Initial design formulas of the strip transmission lines for this purpose are presented, together with some computer simulation results showing the pulse reshaping and compression effects.

I. INTRODUCTION

Picosecond electrical pulses generated from photoconductive switches are finding steadily increasing applications such as microwave and millimeter wave generation[1], on-wafer test of millimeter wave devices[2] and time-domain network analyzers[3]. While the generation and measurements of these ultrafast pulses have been studied extensively, the development of suitable transmission systems capable of handling the enormous bandwidths of these signals remains an important problem[4] and has been the subject of a number of researches during the recent years[5-7].

The dispersion of picosecond electrical pulses on microwave strip transmission lines has been reported by several authors[8-10], mainly from the viewpoint how these ultrashort signals are distorted as they travel along the dispersive transmission lines. On the other hand, positive utilization of the dispersion properties in the transmission and controlling of these short pulses has hardly been studied closely. Li et al had noted in their paper the sharpening effect of a single-sided exponential pulse traveling along microstrip lines[8]. This phenomenon has been investigated in greater detail here, with special attention to the influence of dispersion on the phase distortion of the signal pulses. It is found that microwave transmission lines, such as microstrips and coplanar waveguides, possess similar properties to that of a phase equalizer[11], and can be used to correct the phase distortion included in an asymmetric electrical pulse. At a certain distance along the transmission line, the pulse becomes almost symmetric in waveform, and its FWHM is several times smaller than that of the original pulse. This may provide an alternative to ion implantation or proton bombardment in obtaining pulses with short falling edges, where in the latter cases the transform efficiency of the switch usually drops considerably along with a reduced carrier lifetime of the photoconductive material[12].

II. ANALYSIS

In our analysis we first study the Fourier spectrum of a single-sided exponential pulse as shown in Figure 1(a), which is typical of some photoconductive switches. The phase of the signal, as shown in Figure 1(b), is a nonlinear function of frequency, which indicates that there is a phase distortion included in the signal pulse. If we define $f_{0.1}$ as the frequency where the amplitude of the spectrum is 10 percent of the peak value, we can approximate the phase function ϕ with the following polynomial:

$$\phi = a_1\frac{f}{f_{0.1}} + a_2\left(\frac{f}{f_{0.1}}\right)^2 + a_3\left(\frac{f}{f_{0.1}}\right)^3 + 0(f^4) \qquad (1)$$

for $f<f_{0.1}$. When terms of higher orders are neglected, the nonlinear part, or phase distortion of ϕ, is mainly due to the second and third order terms. If these two terms can be diminished by proper phase compensation, the signal phase will become a linear function of frequency f and reconverting the signal to the time domain will give the Fourier transform limit pulse as shown in Figure 2(a), which is symmetric in waveform and has the narrowest pulsewidth for a given spectral envelope. As will be shown below, a piece of dispersive strip transmission line can be designed to compensate the distortion in the phase spectrum, resulting in effective reshaping and compression of the pulse.

The dispersion characteristics of various types of transmission lines, such as microstrips, coplanar waveguides, coplanar strips and coupled slotlines, have been studied in great detail by many authors. For computer analysis, a simple approximate formula developed by Yamashita et al[13] has been widely used. We rewrite the formula here in the following general form, which is valid for all the abovementioned types of transmission lines:

$$\frac{\beta}{\beta_0} = \frac{\sqrt{\varepsilon_r} - \frac{\beta_{TEM}}{\beta_0}}{1 + aF^{-b}} + \frac{\beta_{TEM}}{\beta_0} \qquad (2)$$

where $F=f/f_{TE}$ is the normalized frequency, $f_{TE}=c/4d\sqrt{\varepsilon_r-1}$ is the cut-off frequency for the lowest order TE mode, β_{TEM} is the

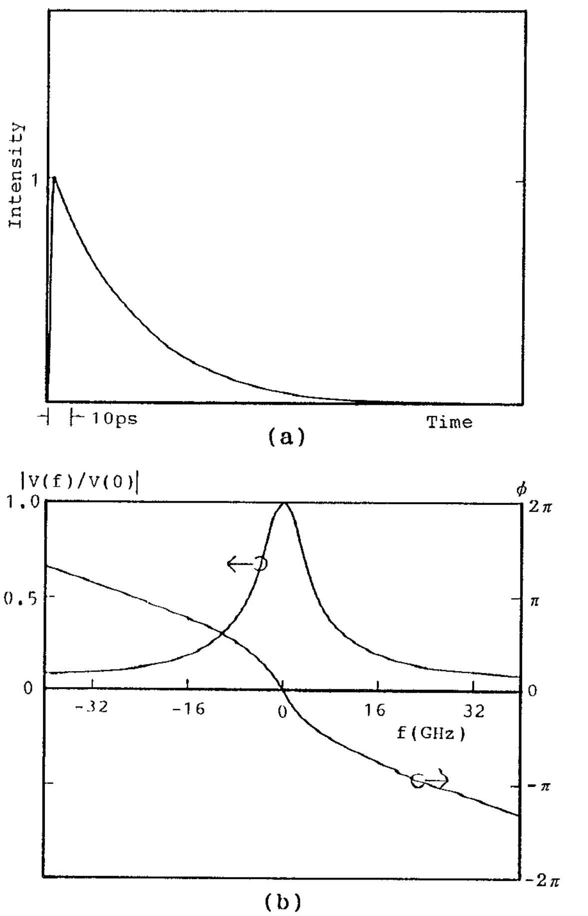

Fig. 1 (a) Single-sided exponential pulse and (b) its Fourier spectrum.

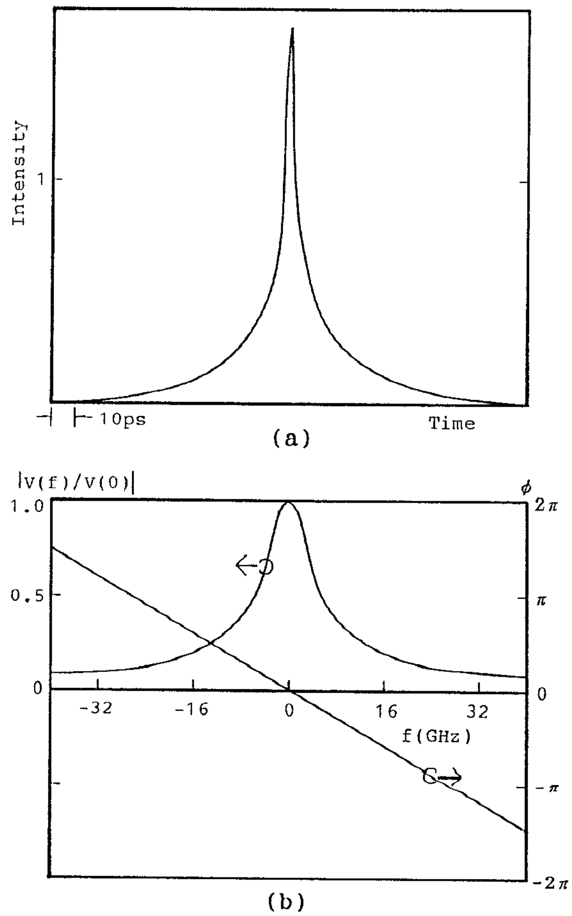

Fig. 2 (a) Fourier transform limit pulse with the same spectral envelope as that of Fig. 1 and (b) its Fourier spectrum.

propagation constant assuming TEM approximation, and a, b are constants which depend on the type and dimension of the transmission line, and can be obtained by curve-fitting the dispersion data calculated with numerical methods.

When a signal pulse propagates along the transmission line, it experiences a continuous phase delay which is expressed as follows:

$$\psi = \frac{2\pi f L}{c} \cdot \frac{\beta}{\beta_0} \quad (3)$$

where L is the propagation distance. To describe the phase compensation effect, it is desirable that the phase delay ψ be expanded in a similar way to that of Eq. (1). Since in Formula (2) the dispersion at f=0 is not defined, we make the Taylor's series expansion at F=1 as:

$$\frac{\beta}{\beta_0} = (\sqrt{\varepsilon_r} - \frac{\beta_{TEM}}{\beta_0})\{\frac{1}{a+1} + \frac{ab}{(a+1)^2}(F-1) + \frac{ab(ab-a-b-1)}{2(a+1)^3}(F-1)^2 + 0[(F-1)^3]\} + \frac{\beta_{TEM}}{\beta_0} \quad (4)$$

for $|F-1|<1$. Consequently

$$\psi = b_1 f + b_2 f^2 + b_3 f^3 + 0(f^4) \quad (5)$$

for $0<f<2f_{TE}$, where

$$b_1 = \frac{2\pi L}{c}[\frac{\beta_{TEM}}{\beta_0} + (\sqrt{\varepsilon_r} - \frac{\beta_{TEM}}{\beta_0}) \cdot \frac{2(a+1)^2 - 3ab(a+1) + ab^2(a-1)}{2(a+1)^3}] \quad (5a)$$

$$b_2 = \frac{2\pi Lab[2(a+1) - b(a-1)]}{cf_{TE}(a+1)^3}(\sqrt{\varepsilon_r} - \frac{\beta_{TEM}}{\beta_0}) \quad (5b)$$

and

$$b_3 = \frac{\pi Lab(ab-a-b-1)}{cf_{TE}^2(a+1)^3}(\sqrt{\varepsilon_r} - \frac{\beta_{TEM}}{\beta_0}) \quad (5c)$$

Comparing Eq. (5) with Eq. (1), we find that if the second and third order terms in the two series are equal to each other, the total phase of the signal after propagating a distance L becomes

$$\phi' = (\frac{a_1}{f_{0.1}} - b_1)f + 0(f^4) \quad (6)$$

which is close to a linear function of frequency f. Taking a reverse FFT, we will obtain a pulse similar to the Fourier transform limit pulse as shown in Figure 2(a). By equating b_2 and b_3 in Eq. (5) to their corresponding coefficients in Eq. (1), we obtain the cutoff frequency f_{TE} and optimum length L_{opt} of the strip transmission line as follows:

$$f_{TE} = \frac{f_{0.1}a_2[b(a-1) - (a+1)]}{2a_3[2(a+1) - b(a-1)]} \quad (7a)$$

and

$$L_{opt} = \frac{ca_2 f_{TE}(a+1)^3}{2\pi ab f_{0.1}^2(\sqrt{\varepsilon_r} - \frac{\beta_{TEM}}{\beta_0})[2(a+1) - b(a-1)]} \quad (7b)$$

Once the cutoff frequency f_{TE} is known, the dimension of the transmission line, mainly the substrate thickness d, can be easily determined from the relations $f_{TE}=c/4d\sqrt{\varepsilon_r-1}$. By changing the constants a and b, the above design formulas are valid for a number of transmission lines, including microstrip lines, coplanar waveguides and coplanar strips[9].

III. SIMULATION RESULTS

To confirm the pulse reshaping and compression effects discussed in the previous section, a computer program has been written to simulate the pulse propagation along a strip transmission line. We follow the same procedures of Li et al[8]. The input pulse shown in Figure 1(a) is expressed as follows:

$$V(0,t) = \begin{cases} V_0 e^{-4\ln 2(\frac{t}{\tau_1})^2} & t<0 \\ V_0 e^{-\frac{t}{\tau_2}} & t>0 \end{cases} \quad (8)$$

A forward FFT transforms the input pulse to its Fourier spectrum $V(0,\omega)$. Multiplying this by the propagation factor $e^{-j\beta(\omega)L}$ and taking a reverse FFT will result in V(L,t), the pulse waveform at a propagation distance L.

Attenuation of the transmission line has been neglected here. Since the propagation distance is within a few centimeters in most of the cases we considered, however, this should not become a serious problem. In fact, the effect of attenuation on pulse distortion is less significant and it only reduces the pulse amplitude slightly, while the waveform of the pulse remains almost the same compared to the case with no attenuation[14].

As an example, a pulse with a 2ps risetime and a total FWHM of 35ps is used as the input signal. Taking a forward FFT we obtain the phase ϕ as well as amplitude V(0,f) of the spectrum as shown in Figure 1(b). The coefficients a_1, a_2 and a_3 in Eq. (1) can be derived by least-square curve-fitting of the FFT data and are obtained to be -7.29, 6.96 and -3.37, respectively. Assuming a 50-Ω microstrip line on GaAs substrate, we have ε_r=12.9, β_{TEM}/β_0 =2.91, a=0.94 and b=1.5[13]. Using Formula (7a), the cutoff frequency f_{TE} is calculated to be 16.9GHz, which corresponds to a substrate thickness of d=1.3mm. Applying Formula (7b), we obtain the optimum length of the microstrip line L_{opt}=11mm. Computer simulation results of pulse propagation along the designed microstrip line are shown in Figure 3. It is clear that near L_{opt} the pulse is closest in waveform to that of the Fourier transnform limit pulse shown in Figure 2(a). The FWHM of the compressed pulse is 9ps, which is about four times narrower than that of the original pulse. Further propagation along the microstrip line will again distort and broaden the pulse.

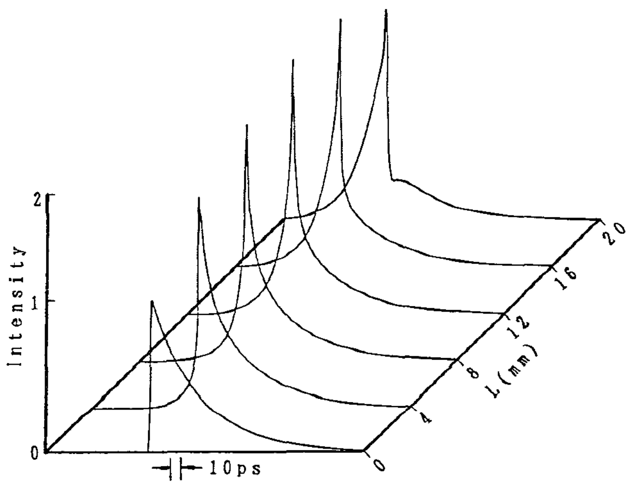

Fig. 3 Simulation results of the propagation of a 35ps single-sided exponential pulse along 50-Ω microstrip lines on GaAs substrate.

IV. CONCLUSIONS

The propagation of picosecond electrical pulses on strip transmission lines has been investigated with special attention to the phase compensation effect of the dispersion properties of the transmission lines. With a careful selection of the type, dimension and length of the transmission line, asymmetric picosecond electrical pulses can be reshaped and compressed effectively to be close to their Fourier transform limit.

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References

[1] D. Butler et al, Microwave and Optical Technology Lett., vol.1, No.4, pp.119-123, June 1988.

[2] R. Majidi-Ahy et al , IEEE MTT-S Digest, pp.299-302, 1989.

[3] K. J. Webb et al, IEEE MTT-S Digest, pp.217-220, 1989.

[4] C. H. Lee, Picosecond Optoelectronic Devices (New York: Academic Press, 1984), Chapter 4, pp.73-116.

[5] D. H. Auston et al, Appl. Phys. Lett., 45(3), pp.284-286, Aug. 1984.

[6] A. P. Defonzo et al, Appl. Phys. Lett., 51(4), pp.212-214, July 1987.

[7] J. F. Whitaker et al, IEEE Trans. on MTT, vol. MTT-36, pp.277-285, Feb. 1988.

[8] K. K. Li et al, IEEE Trans. on MTT, vol. MTT-30,pp.1270-1273, Aug. 1982.

[9] G. Hasnain et al, IEEE Trans. on MTT, vol. MTT-34, pp.738-741, June 1986.

[10] J. F. Whitaker et al, IEEE Trans. on MTT, vol.MTT-35, pp.41-47, Jan. 1987.

[11] S. O. Scalan et al, IEEE Trans. on MTT, vol. MTT-16,pp.62-79, Feb. 1968.

[12] A.G. Foyt et al, Appl. Phys. Lett., 40(6), pp.447-449, Mar. 1982.

[13] E.Yamashita et al,IEEE Trans. on MTT, vol. MTT-27, pp.1036-1038, Dec. 1979.

[14] T. Leung et al, IEEE Trans. on MTT, vol. MTT-36, pp.765-769, Apr. 1988.