Distortion of Pulsed Signals in Microstrip Transmission Lines Using Short-Time Fourier Transform

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***Abstract*—Short-time Fourier transform (STFT) is used to window the propagation of pulses traveling in microstrip lines. Characteristics of dc and Gaussian pulses are studied based on their zoom-in time-amplitude windows, fast Fourier transforms, and time-frequency results. Behaviors of dc and Guassian pulses at a certain time along the length of a microstrip line are also examined. The STFT technique can be used to observe the distortion locally at any time and at any point in the microstrip lines and is especially attractive when the microstrip lines are subjected to complex signals, which vary substantially over a short duration.**

I. INTRODUCTION

ANY pulsed signal traveling along transmission lines gets distorted, and the distortion becomes significant when the wavelength becomes comparable to the transmission lines' cross-sectional dimensions and when the high-frequency and low-frequency components of the pulse travel with different velocities. The distortion information is important in the design of microwave and millimeter-wave hybrid integrated circuits (MIC's) and monolithic integrated circuits (MMIC's). Distortion has received much attention in the past decade, e.g. [1]–[4]. In these works, distortion of pulses in transmission lines was calculated using the conventional Fourier transform along with the effective dielectric constants obtained from the spectral-domain method or the closed-form expressions.

In this letter, short-time Fourier transform (STFT) is applied to determine the distortion of pulses in microstrip lines. The main advantage of STFT is that it can localize at any time and at any point along the length of the transmission line to zoom in. This allows one to closely examine the signal behavior at any instant. This advantage is apparent when the microstrip lines are subjected to complex signals that vary widely over a short duration. With the conventional Fourier-transform methods, which treat all the time periods equally, we cannot analyze the behavior of the pulses during those short durations when they are subjected to wide variations. Using the concept of STFT, we are able to localize the distortion of Gaussian and dc pulses along the length of a microstrip line. STFT has been used in analyzing scattering problems, e.g. [5].

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II. THEORY

The time-domain representation of a signal traveling in a lossless microstrip line at a distance L is given as [4]

$$f(t,L) = \frac{1}{2\pi}\int_{-\infty}^{\infty} \hat{f}(w, z=0)e^{j[wt-\beta(w)L]}dw$$

where the phase constant $\beta(w)$ is obtained as

$$\beta(w) = \frac{w}{c}\sqrt{\varepsilon_{\text{reff}}}$$

with $\varepsilon_{\text{reff}}$ and c being the effective dielectric constant and free-space velocity, respectively. $\hat{f}(w)$ represents the Fourier transform of the signal as

$$\hat{f}(w) = \int_{-\infty}^{\infty} f(t)e^{-jwt}dt.$$

In implementing the STFT technique, a window for localization purposes needs to be chosen. Here, the optimal window for localization is obtained using any Gaussian function

$$g_\alpha(t) = \frac{1}{2\sqrt{\pi\alpha}}e^{-\frac{t^2}{4\alpha}}$$

where α is fixed as the window function and determines the width of the window. For any value of $\alpha > 0$, we now define the Gabor transform as [6]

$$G_b^\alpha f(\omega) = \int_{-\infty}^{\infty} f(t)g_\alpha(t-b)e^{-jwt}dt.$$

That is, $(G_b^\alpha f)(w)$ localizes the Fourier transform of the signal $f(t)$ around $t = b$. Alternatively, $(G_b^\alpha f)(w)$ can be represented as

$$G_b^\alpha f(w) = \int_{-\infty}^{\infty} f(t)\overline{G_{b,w}^\alpha(t)}dt$$

where

$$(G_{b,w}^\alpha f)(t) = e^{jwt}g_\alpha(t-b).$$

$G_{b,w}^\alpha$ is plotted in Fig. 1 for $\alpha = 0.2925$. Instead of considering $G_b^\alpha f$ as a localization of the Fourier transform of f, we may interpret it as windowing the function f by using the window function $G_{b,w}^\alpha$. One advantage of the above formulation is that Parseval's identity can be applied to relate the Gabor transforms of f and f, since [6]

$$(G_b^\alpha f)(w) = \frac{e^{-jbw}}{2\sqrt{\pi\alpha}}(G_w^{\frac{1}{4\alpha}} f)(-b)$$

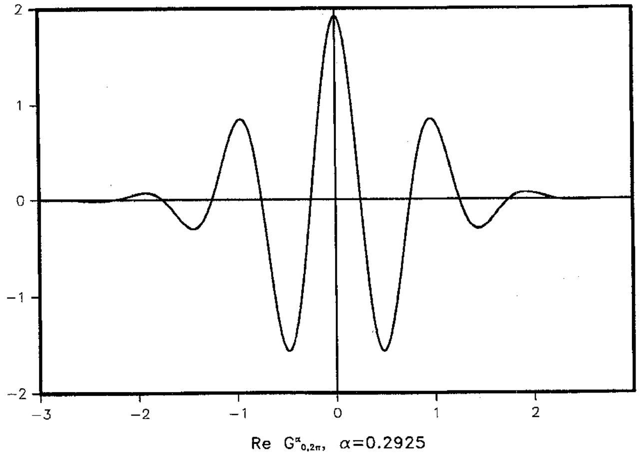

Fig. 1. Real part of the Gabor transform $G^{\alpha}_{b,w}$ for $\alpha = 0.2925$, $b = 0$, and $w = 2\pi$.

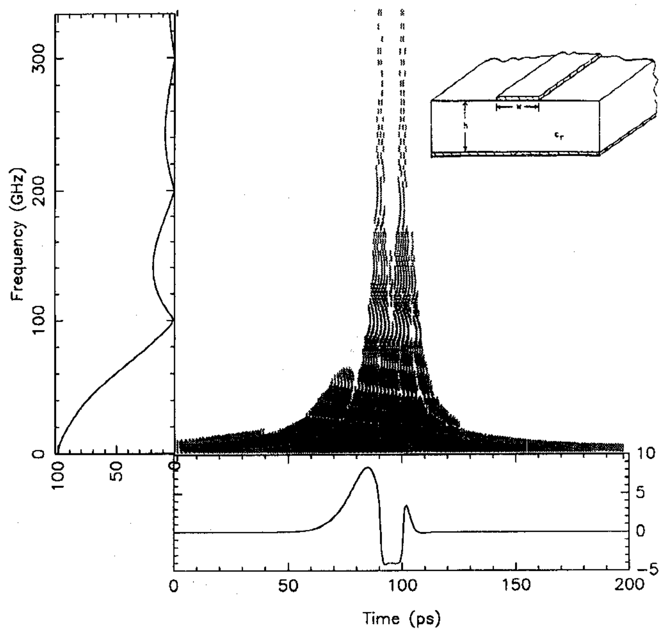

Fig. 2. Time and frequency responses of a 20-ps rectangular dc pulse in a microstrip line at $L = 0.354$ in.

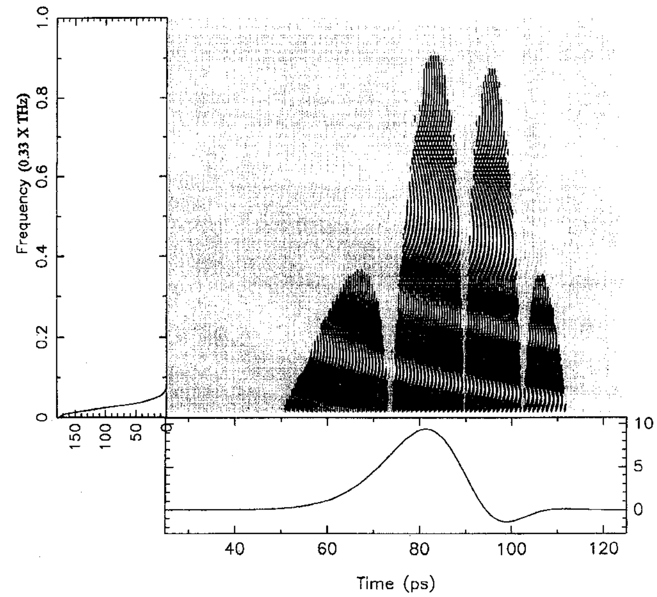

Fig. 3. Time and frequency responses of a 20-ps Gaussian pulse in a microstrip line at $L = 0.354$ in.

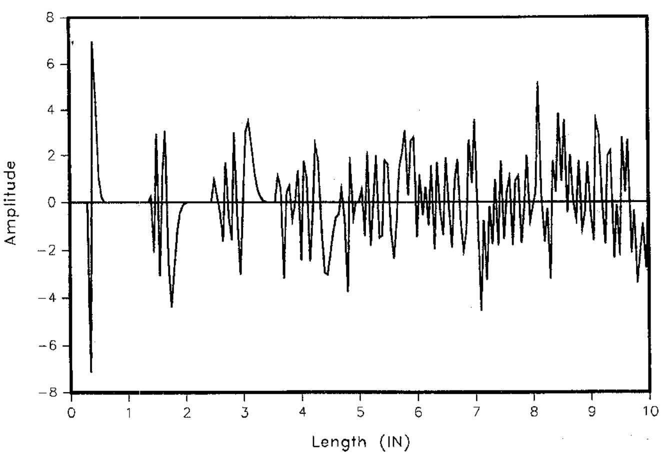

Fig. 4. Propagation of a 20-ps rectangular dc pulse along a microstrip line at a fixed time of 100 ps.

which can be interpreted as the window Fourier transform of f, with the window function $g_{\alpha}(t)$ at $t = b$ agreeing with the window inverse-Fourier transform of f with window function $g_{1/4\alpha}$ at $\eta = w$, where η is the variable in the Fourier-transform domain.

It should be noted here that the maximum distance, in which the calculations are valid for a single pulse, is limited by the fact that the low-frequency components of a pulse catch up with the high-frequency components of the previous pulse and is given by

$$L = \tau \frac{c}{\sqrt{\varepsilon_{\text{reff}}}[\sqrt{\varepsilon(\infty)} - \sqrt{\varepsilon(0)}]}$$

where τ is the time period of the pulse, $\varepsilon(\infty)$ and $\varepsilon(0)$ are the limiting values of the effective dielectric constants at the high and low frequencies, respectively.

III. Numerical Results

Figs. 2 and 3 show the time and frequency behaviors of rectangular dc and Gaussian pulses having 3-dB 20-ps pulse widths in a lossless microstrip line with $w/h = 1$ and $\varepsilon_r = 9.9$ at $L = 0.354$ in., calculated using the developed theory. These waveforms were computed using numerical integration. The microstrip line's structure is shown in Fig. 2's insert; its effective dielectric constant was obtained using the closed-form expression given in [7]. The bottom plots of Figs. 2 and 3 show the whole dispersed signals zoomed in in the time-amplitude window [8], while those in the left are the fast Fourier transforms of these signals. The central figures are the three-dimensional time-frequency responses using the wavelets [6], which display the intensities of time as well as frequency components of the signals. It can be observed, in the time-frequency plots, that concentration of the signals is more at the low frequency range and the dc signal (band-unlimited) decays exponentially while the gaussian signal (band-limited) vanishes at high frequencies.

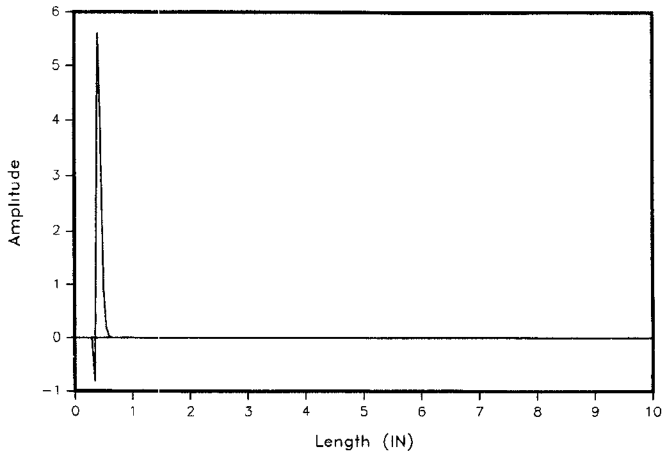

Fig. 5. Propagation of a 20-ps Gaussian pulse along a microstrip line at a fixed time of 100 ps.

Figs. 4 and 5 depict the propagation behavior of the above-mentioned pulses at $t = 100$ ps along the whole length of the microstrip line $(w/h = 1, \varepsilon_r = 9.9)$. It can be observed that the propagating dc pulse at a particular instant exists over the entire length, while the traveling Gaussian pulse only appears at the location corresponding to the time. These behaviors are due to the dispersive natures of the pulses. They can be explained by the spectral properties of the pulses, as we know that the dc pulse spreads through the whole gamut of the domain while the Gaussian pulse is band-limited in both the time and frequency domain.

IV. Conclusion

STFT has been employed to study the propagation of pulses in microstrip lines. The STFT method is useful for closely examining the local distortion at any time and at any point in the microstrip lines. It is especially attractive when the applied signals are complex and vary widely over a small duration. The propagation of pulsed signals traveling along a microstrip line, obtained using the developed technique, are important, as they can be used to determine the signals' switching and transient behavior, which can then be employed in the design of MIC's and MMIC's.

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