# Demonstrated low radiative loss of a quadrupole ultrashort electrical pulse propagated on a three strip coplanar transmission line

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We present an approach for reducing the absorption and dispersion due to Cherenkov radiation on coplanar transmission lines, which does not require the reduction of the permittivity mismatch between the substrate and the superstrate of the optoelectronic chip. Exciting only the odd mode of a three strip coplanar transmission line, a quadrupole ultrashort electrical pulse is generated and propagates with very low radiative loss over long distances (>5 mm). The quadrupole's measured frequency dependent absorption and dispersion, are compared to those measured for the even mode (dipole) pulse on the same transmission line. The radiative loss for the quadrupole pulse is shown to be <1/10 that of the dipole pulse, and for equal transverse dimensions it is <1/10 the radiative loss of the two strip transmission line and of the two slot coplanar waveguide. © *1997 American Institute of Physics.* [S0003-6951(97)01945-1]

The loss mechanisms involved in the propagation of ultrashort electrical pulses on coplanar transmission lines (CTLs) have been studied extensively by several groups utilizing optoelectronic sampling techniques.[1–6] For such electrical pulses, Grischkowsky *et al.*[4] have shown that the main absorption loss at the lower frequencies (<200 GHz) is through conduction losses in the lines ($\propto \sqrt{f}$, where $f$ is the frequency), whereas the high frequency absorption is predominantly due to an electromagnetic shock wave radiation loss mechanism ($\propto f^3$) similar to Cherenkov radiation. Later work by Frankel *et al.*,[6] shows that in the full wave analysis approach to the analytical equation for the absorption, the effective dielectric constant is also slightly frequency dependent, modifying the absorption from a strict $f^3$ dependence. Overall, it is this radiative loss that is responsible for the rapid broadening of the ultrashort electrical pulses since it radiates energy from the high frequency components.[4] In brief, the shock wave is generated because the pulse on the line travels significantly faster than the phase velocity in the dielectric substrate. This velocity mismatch is a direct result of the permittivity mismatch between the substrate and air.

In attempts to reduce the permittivity mismatch, a variety of transmission line structures have been designed. The ideal transmission line would have no substrate/superstrate mismatch. Along these lines, Dykaar *et al.* fabricated coplanar air transmission (CAT) lines, which are two-strip CTLs edge supported by a 200 nm layer of $SiO_2$ on GaAs.[7] The GaAs below the transmission line is etched away leaving the striplines supported in free space. Rise times as short as 0.8 ps after a propagation length of 2.8 mm were obtained. CTLs have also been fabricated on low permittivity substrates and membranes, on the order of microns thick, demonstrating significantly reduced loss and higher bandwidths.[8–10]

In this letter we present an approach to the reduction of radiative loss from ultrafast CTLs, where no attempt is made to reduce the permittivity mismatch. For this case, the mode characteristics of a three-strip coplanar stripline (CPS) are utilized to generate a quadrupole ultrashort electrical pulse with significantly reduced absorption and dispersion. In general the number of allowed propagating modes for a transmission line is one less than the number of wires in the line, i.e., a three-line transmission line has two modes, the even and odd mode. Through appropriate bias of the striplines [Fig. 1(a)] either the even mode, where the electric fields between each gap are parallel, or the odd mode, which has the electric fields in the gaps antiparallel, is exclusively excited. The even mode has a two-dimensional (2D) dipole field distribution in the plane perpendicular to the CTL and the odd mode has a 2D quadrupole field pattern. These different distributions exhibit substantially different loss properties. Cheng *et al.*[10] demonstrated the superposition of even and odd modes on a two-slot coplanar waveguide (CPW).

Utilizing ultrashort optical pulses to excite an ultrashort electrical pulse, i.e., spatially localized along the transmission line, a 3D multipole moment (3D dipole or 3D quadrupole) is excited on the lines which propagates along the three-strip CPS. The electric field associated with each increasing order multipole moment, falls off more rapidly with distance.[11] In the far field the ideal 3D dipole field decreases as $r^{-3}$ whereas the ideal quadrupole field decreases as $r^{-4}$. Due to this more rapid fall of the quadrupole electric field distribution, the absorption and dispersion of the guided quadrupole pulse is significantly reduced. Here we present experimental data comparing the frequency dependent absorption and dispersion of the dipole and quadrupole ultrashort electrical pulses on the same three-strip CPS, thereby giving a valid comparison of ultrashort quadrupole pulse propagation to the dipole pulse propagation.

The commonly used two-slot CPW, consisting of a line centered between two ground planes, also has a quadrupole mode. Due to the two-ground planes, for the same transverse dimensions the two-slot quadrupole mode transversely extends much further than the three-strip quadrupole mode. Consequently, the radiative loss of the two-slot quadrupole

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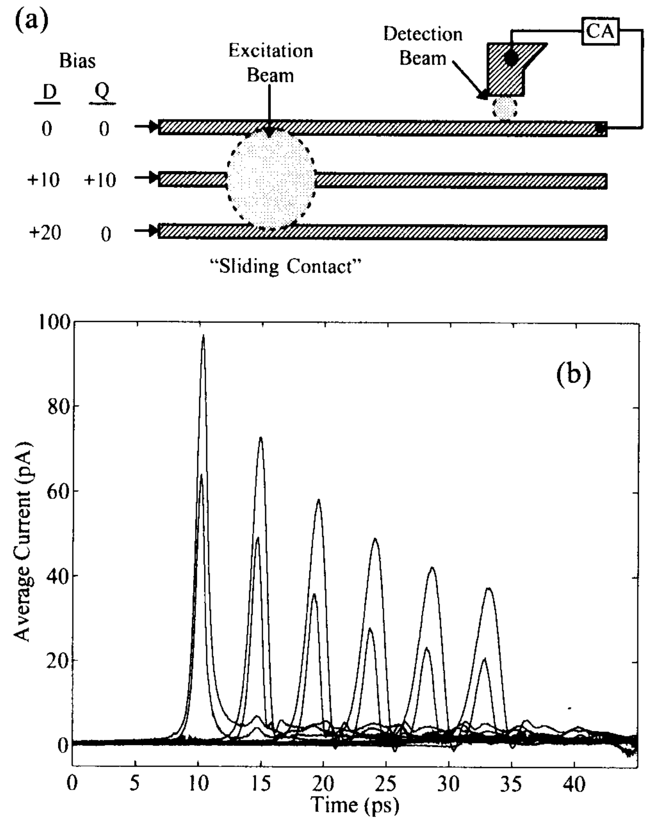


FIG. 1. (a) Three-strip coplanar transmission line with sliding contact excitation and side gap detection. The aluminum strip lines are 4-$\mu$m-wide separated by 15 $\mu$m. Ultrashort quadrupole electrical pulses are generated with bias $Q$, dipole pulses with bias $D$. CA: current amplifier. (b) Measured quadupole (lower curves) and dipole (upper curves) electrical pulses at propagation lengths of 0.2, 1.2, 2.2, 3.2, 4.2, and 5.2 mm.

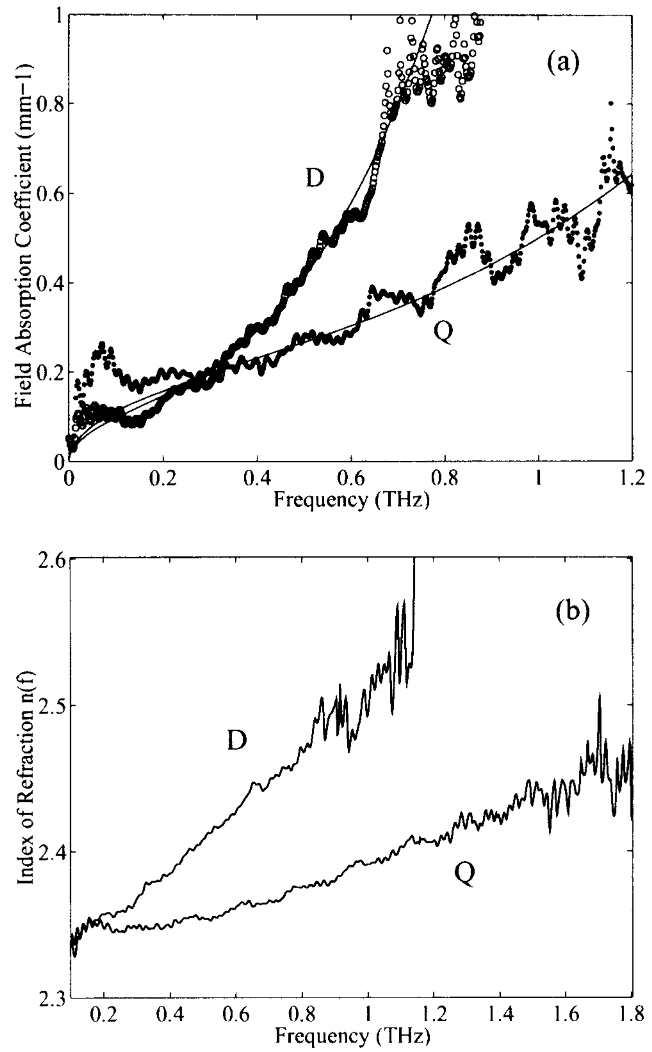


FIG. 2. (a) Measured field absorption coefficient overlaid with the fit to the data for (Q) quadrupole (odd mode) and (D) dipole (even mode) pulses. (b) Measured index of refraction for the (Q) quadrupole (odd mode) and (D) dipole (even mode) pulses.

mode has been calculated to be comparable to that of the two-strip CPS.[6,10,12] Our measurements show these losses are an order of magnitude larger than the measured radiation loss of the quadrupole mode of the three-strip CPS.

Our three-strip CPS was fabricated on an undoped silicon on sapphire wafer, which was heavily implanted with $O^+$ ions to insure the required short carrier lifetime.[13] The ultrashort electrical pulse generation is done using the "sliding contact" technique with a 70 fs pulse from a Ti:Sapphire laser running at 830 nm and focused to a 36 $\mu$m diam spot to simultaneously illuminate both gaps. The generated pulse is detected at a stationary pickoff pad, with a side gap of 10 $\mu$m, that is photoconductively shorted with a second time delayed laser pulse. Electrical pulse propagation distances to 5.2 mm can be obtained without end reflection effects. The setup is changed from the dipole to the quadrupole mode by simply changing the direction of the applied bias field (10 V) on the striplines. No adjustment to the optical beams is necessary to change the configuration from dipole to quadrupole. Measurements of the electrical pulses were obtained by scanning a computer controlled mechanical delay line with 0.1 $\mu$m resolution. The laser excitation beam was mechanically chopped at 2 kHz and the electrical signal was detected with a current amplifier and a digital lock-in amplifier.

A series of ultashort electrical pulse data for both the dipole and quadrupole configurations is shown in Fig. 1(b), with pulse propagation distances from 0.2 to 5.2 mm in increments of 1 mm. The quadrupole pulses are the smaller narrower set of pulses. Since the signal detection is by a side gap, the electric field adjacent to the stripline is detected. Therefore, the different initial signal strengths for the two cases demonstrates that the quadrupole has a smaller electric field in the substrate. Due to the nature of the experimental setup for the sliding contact technique, the relative time delay between the depicted electrical pulses is: $\Delta t = z(n_{\mathrm{eff}} - n_{\mathrm{air}})/c$, where $z$ is the propagation distance, $n_{\mathrm{eff}}$ is the effective index of refraction for the transmission line, and $c$ is the speed of light. This yields $n_{\mathrm{eff}} = 2.35$, compared to 3.07 for the fast axis of the crystalline sapphire substrate. The pulses propagate with a speed of $c/n_{\mathrm{eff}} = 0.43c$.

To completely characterize the two modes of the three-strip CPS. Fourier analysis is used to transform the time domain data into the frequency domain. From these data the absorption and dispersion of the propagating ultrashort electrical pulse is obtained. For both the dipole and quadrupole mode, the pulse with the shortest propagation distance, $z = 0.2$ mm, is used as the reference pulse, $E_r(\omega)$, where $\omega$

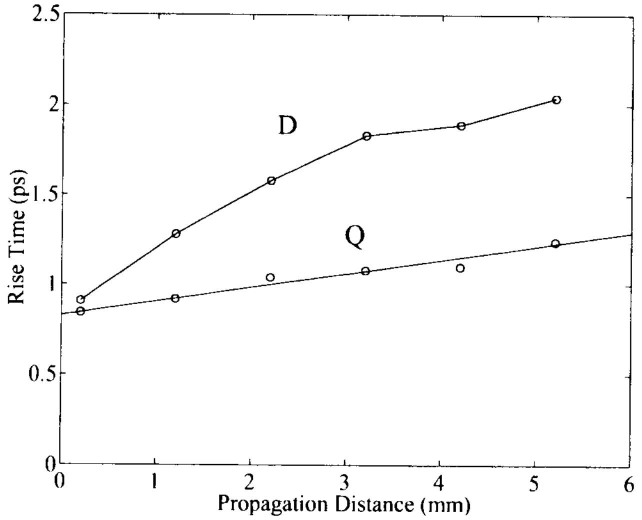


FIG. 3. Rise time (10%–90%) comparison of the three strip line (Q) quadrupole (odd mode) with (D) dipole (even mode).

$=2\pi f$ is angular frequency. The signal pulses, $E_z(\omega)$, are the set of pulses with propagation distances from 1.2 to 5.2 mm. The frequency dependent electric field of the signal is $E_z(\omega)=E_r(\omega)e^{ik(\omega)z}e^{-\alpha(\omega)z}$. Here $\alpha(\omega)$ is the field absorption coefficient and $k(\omega)$ is the wave vector. The frequency dependent index of refraction is given by $n(\omega)=k(\omega)c/\omega$.

The field absorption coefficient $\alpha(f)$ for the quadrupole pulse (odd mode), and the dipole pulse (even mode) on the three-strip CPS are shown in Fig. 2(a). Each plot is the average of the results for the five propagation distances. The absorption for the quadrupole is dramatically reduced over that of the dipole; at 0.8 THz a factor of 2 difference between the two coefficients is observed. Both curves are fit with the mathematical relationship $\alpha(f)=A_{res}f^{1/2}+A_{rad}f^3$, where the resistive ($A_{res}$) and the radiative ($A_{rad}$) loss coefficients are free parameters and $f$ is the unitless magnitude of the frequency in THz, i.e., $f=1$ corresponds to 1 THz.[4] This relation fits both curves reasonably well, with the two resistive coefficients having values that agree to within about 15%. For the dipole pulse $A_{res}$ is 0.3 $\mathrm{mm}^{-1}$, compared to 0.35 $\mathrm{mm}^{-1}$ for the quadrupole. However, a very large difference is observed in the two radiative coefficients. For the dipole pulse, the strong $f^3$ dependence is seen with the radiative coefficient $A_{rad}=1.6$ $\mathrm{mm}^{-1}$, whereas the quadrupole pulse has the much smaller coefficient $A_{rad}=0.15$ $\mathrm{mm}^{-1}$. This order of magnitude reduction clearly demonstrates that for the three-strip CPS the radiative loss for the electric quadrupole pulse is significantly less than that of a dipole pulse. The dipole signal drops below the signal to noise ratio at 0.7 THz, whereas the quadrupole signal extends beyond 1.1 THz. The value of $A_{rad}=1.6$ $\mathrm{mm}^{-1}$ for the three-strip dipole pulse is in good agreement with the expected $A_{rad}$ for a two-strip CPS of the same transverse dimension of $W$ $=42$ $\mu$m. Since $A_{rad}$ is proportional to $W^2$ (Refs. 4 and 12), this can be confirmed by a simple scaling argument using the experimental $A_{rad}=0.65$ $\mathrm{mm}^{-1}$ from Ref. 4, for the two-strip CPS with the transverse dimension $W=25$ $\mu$m. For $W=42$ $\mu$m a value of $A_{rad}=1.8$ $\mathrm{mm}^{-1}$ is obtained, in good agreement with our measurement. This agreement supports the conclusion that the radiation loss for the three-strip CPS dipole pulse is similar to that of the two-strip CPS with the same transverse dimension. The index of refraction for the two modes of the three-strip CPS is plotted for the same set of pulses in Fig. 2(b). The frequency dependent part of the index for the quadrupole pulse is less than one third that of the dipole pulse. The frequency independent part is the same for both modes and is consistent with the measured pulse velocity.

Although the absorption and dispersion completely characterize the propagation of the odd and even modes of the three-strip CPS, in ultrafast circuits the integrity of the pulse rise time versus distance is also major concern. The comparison of the rise time for the dipole and quadrupole pulses versus interaction length is shown by the two curves of Fig. 3. The extrapolated zero distance rise time is 0.8 ps for both the quadrupole and dipole pulses. The initial slope of the dipole is 0.38 ps/mm though it appears to saturate at longer distances. The slope of the quadrupole is quite linear across the whole data set, with a value of 0.08 ps/mm, almost five times smaller than the initial slope of the dipole.

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