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Nature of subpicosecond terahertz pulse propagation in practical dielectric-filled parallel-plate waveguides

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It is analytically shown that the presence of submicrometer-sized air gaps between the dielectric and metal contact surfaces in a dielectric-filled metallic parallel-plate waveguide can have a dramatic effect on the guided-wave propagation of subpicosecond terahertz pulses. Through the use of metal-evaporated dielectric surfaces to overcome the imperfect contact problem, and a special air–dielectric–air cascaded waveguide geometry to avoid multimode excitation, undistorted subpicosecond terahertz pulse propagation via the single-TEM mode is demonstrated, for what is believed to be the first time, in a silicon-filled PPWG. © 2006 Optical Society of America

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Ever since undistorted subpicosecond terahertz pulse propagation was demonstrated using the metallic parallel-plate waveguide (PPWG),[1,2] there has been considerable interest in this type of waveguide for a variety of applications in the terahertz frequency regime. Backed by the simple planar geometry and excellent coupling to free-space radiation, PPWGs have been employed to study whispering-gallery modes,[3] to demonstrate interconnect layers,[4] to study photonic crystals,[5] to generate terahertz radiation,[6] for building biosensing systems,[7] and for guided-wave spectroscopy.[8] Most of these applications have sought to exploit the low loss, dispersionless characteristics of the dominant TEM mode, with the space between the plates filled with air[1,2] or some other form of dense medium such as a dielectric. These have shown that TEM mode propagation can be realized with relative ease in air-filled (AF) PPWGs, whereas there still remain practical difficulties in realizing the same in dielectric-filled (DF) ones.[3,5] To resolve these difficulties and further the potential use of the DF-PPWG, this Letter examines the behavior of this particular structure through the propagation of subpicosecond terahertz pulses.

As in previous experiments,[1,2] a modified terahertz time-domain spectroscopy setup was used to quasi-optically couple subpicosecond terahertz pulses into and out of the waveguides, and measure the electric field of the propagated pulses. Figure 1(a) shows the pulse propagated through a 25 mm long, AF Al PPWG with a plate separation of 100 μm used as a reference waveguide. Figure 2(a) gives the amplitude spectrum (thin solid curve) that extends to approximately 4 THz, derived by Fourier transforming the 0.2 ps (FWHM) pulse. The clean pulse with the smooth spectrum that shows no localized oscillations (multimode interference effects), and no cutoff, confirms single-TEM mode propagation.[1,2] This was despite the higher-order TM_2^A mode, where A denotes air, cutting in at 3 THz. The even-Gaussian input beam, polarized normal to the plates, can excite only the even TM modes.[9]

Figure 1(b) shows the pulse propagated through the Al PPWG with its midsection filled with a 5 mm long, high-resistivity Si slab as shown in the inset.
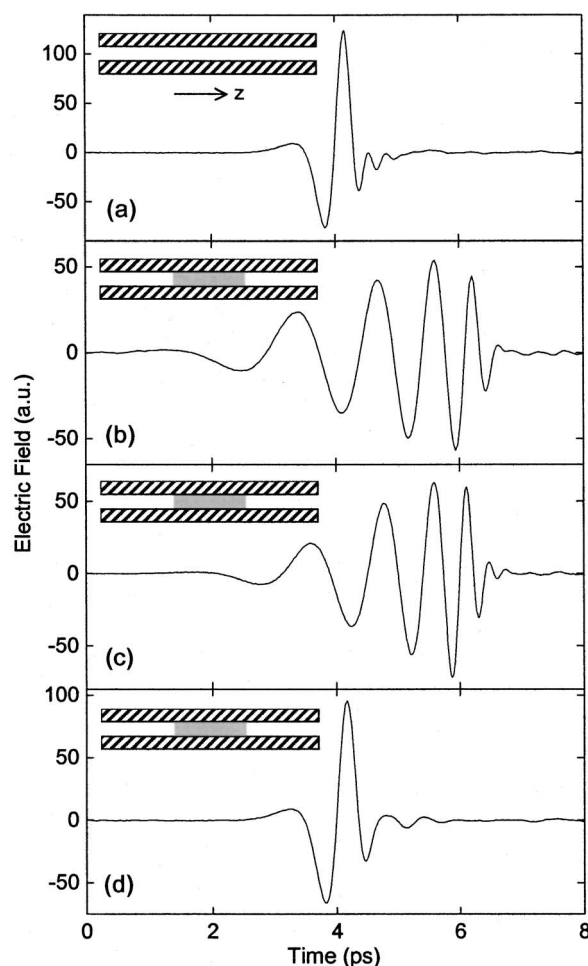

Fig. 1. Propagated pulses through the PPWGs whose axial cross sections are shown in the inset. (a) AF waveguide, (b) waveguide with a DF section, (c) theoretical simulation, and (d) waveguide with a metallized dielectric section. Vertical axes are not to scale. Time zero is arbitrary.
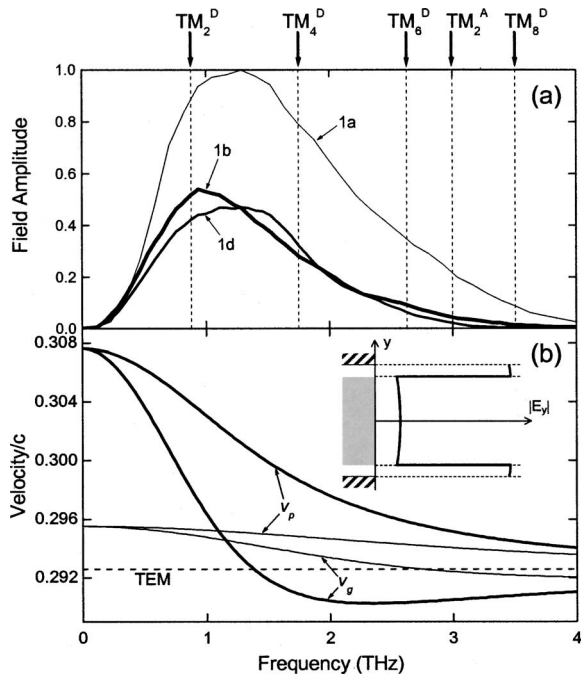
Fig. 2. (a) Amplitude spectra of the measured pulses in Fig. 1. The respective amplitudes are not to the same reference. The dashed vertical lines correspond to higher-order mode cutoff frequencies. (b) Group and phase velocity for the TM_0 mode of the DF-PPWG with 0.5 μm (thick solid curves), and 0.1 μm (thin solid curves) air gaps, compared to that of the TEM mode of the ideal waveguide (dashed line). A typical mode profile is shown in the inset (not to scale).

The 100 μm thick Si slab was tightly sandwiched between the plates to obtain a good physical contact. This air–dielectric–air cascaded waveguide geometry was chosen to ensure single-TEM mode propagation in the DF-PPWG section, as the spatial profile of the TEM mode in the AF sections would be perfectly matched to that in the DF section. This is particularly the case since the DF section was capable of propagating a number of higher-order modes within the experimental bandwidth due to the high refractive index ($n = 3.418$) of Si. For a theoretically ideal DF section, these are the TM_2^D (0.88), TM_4^D (1.75), TM_6^D (2.63), and TM_8^D (3.51) modes, where D denotes dielectric, and the terahertz cutoff frequencies are in parentheses. Despite the favorable geometry, the pulse is highly distorted compared with that in Fig. 1(a), clearly indicating a non-TEM behavior. It is broadened by dispersion and exhibits a positive chirp, where low frequencies have arrived earlier in time. While the corresponding, smooth amplitude spectrum (thick solid curve) in Fig. 2(a) suggests good single-mode behavior via a mode having no cutoff. This startling contradictory behavior calls for a renewed understanding of the guided-wave propagation in this type of DF-PPWG. It was suspected that the physical contact between the dielectric and metal surfaces, perhaps residual air trapped during fabrication, had a role to play in this, and this led to a full modal analysis for a DF-PPWG having air gaps at the contact surfaces.

The guided-wave propagation in this structure, excited by an electric field polarized normal to the plates, can be theoretically analyzed starting from the hybrid mode solutions of a partially filled rectangular waveguide.[10] As illustrated in Fig. 3, the first step in this development is to evolve the rectangular waveguide into a PPWG by removing the x dependence and setting the x dimension of the waveguide to infinity. This reduces the hybrid modes to a pure TM set with E_y, H_x, and E_z as the only possible field components, where z is the direction of propagation. The new structure [Fig. 3(b)] has an air gap at the top dielectric surface. To generalize the structure to the practical case where there are air gaps at both the top and the bottom surfaces, the next step is to use the concept of imaging. Here, the bottom metal plate is considered to act as a mirror for the rest of the guide such that the modal expressions that are valid for this structure [Fig. 3(b)] are also valid for the complete structure made up of the mirror image [Fig. 3(c)]. This analysis reveals that the dominant propagating mode (designated here as TM_0) has no cutoff, but at the same time, is not of the TEM type. The phase constant (β_z) for the propagating modes can be evaluated from the resulting transcendental equation, which can then be used to derive the phase velocity (v_p), the group velocity (v_g), and the mode profile ($|E_y|$).

Theoretical velocity curves are plotted in Fig. 2(b) for the TM_0 mode of a Si-filled PPWG having a plate separation of 100 μm, with 0.5 μm (thick solid curves) and 0.1 μm (thin solid curves) air gaps. The constant, frequency-independent velocity ($=c/n$) associated with the TEM mode of an ideal (no air gaps) Si-filled waveguide is also shown (dashed line). These plots indicate a clear deviation from TEM mode behavior due to the presence of the air gaps. Considerable dispersion is associated with even submicrometer-sized air gaps, which increases with increasing gap size (Δh). The group velocity dispersion will cause low-frequency components of a pulse to propagate faster, producing the observed positive chirp. Toward the high-frequency end, the velocities approach the TEM mode value. The physical origin of
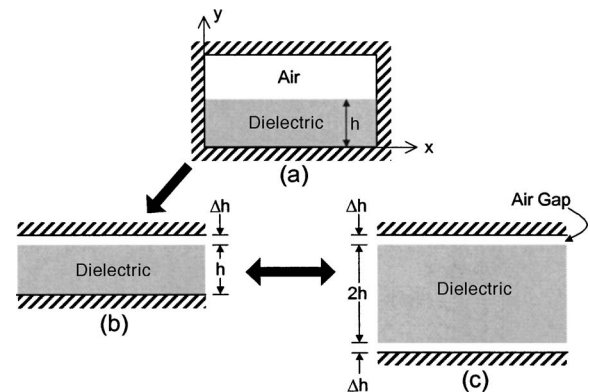

Fig. 3. Transverse cross-sectional views of the DF waveguides used for the theoretical development. Cross-hatched areas indicate metal. (a) Partially filled rectangular waveguide, (b) PPWG with an air gap at the top plate, and (c) PPWG with air gaps at top and bottom plates.

the dispersion is related to the changeover in the spatial power flow that becomes more confined to the dielectric part as the frequency increases, similar to the case of a dielectric-coated metal-wire waveguide.[11] The typical mode profile (shown in the inset) indicates that the electric field intensity in the gaps is much greater than in the dielectric, with the discontinuity at the dielectric–air interface equal to n^2 (the ratio). For submicrometer air gaps, the central portion of the profile spans most of the plate-to-plate distance, and is well matched to the flat-top profile of a TEM mode. This explains the coupling between the AF and DF sections of the structure in Fig. 1(b).

The guided-wave model was tested by theoretically simulating the propagated pulse using the calculated β_z. The electric field of the propagated pulse can be deduced from the product, $E_{in}(\omega) \times \exp(-j\beta_z L)$, taking only dispersion into account, where $E_{in}(\omega)$ is the input electric field at frequency ω and L is the distance of propagation. As it was not possible to exactly physically model the air gaps, Δh was used as a floating parameter, while taking $L = 5$ mm, the actual length of the slab. The pulse in Fig. 1(a) was used for $E_{in}(\omega)$ since the structure consisted of AF sections, similar to the reference guide, at the input and output ends. Fourier transforming this pulse and carrying out the above product in the frequency domain using the calculated β_z for the TM_0 mode, and then inverse-Fourier transforming to the time domain, gives the simulated pulse. This is shown in Fig. 1(c) where $\Delta h = 0.5 \ \mu$m, clearly resembling the experimentally observed pulse in Fig. 1(b), despite the exclusion of losses. This agreement strengthens the validity of the guided-wave model, and strongly points to submicrometer air gaps at the contact surfaces as having caused the observed non-TEM behavior. It is interesting to note that in a previous study employing a DF-PPWG, a similar positively chirped terahertz pulse has been observed, which has been attributed to a multimode effect due to the larger thickness of the dielectric (Si) slab.[5] Although multimode excitation is a possibility, based on the guided-wave model presented here, it is more likely that this chirped behavior was caused by the excitation of the TM_0 mode due to imperfect surface contacts.

To solve the imperfect contact problem, the Si slab was plasma cleaned and metallized on both surfaces by thermal evaporation of Al. Figure 1(d) shows the pulse propagated through the same Al PPWG as used before, but this time with its midsection sandwiching a 4 mm long metallized Si slab. This pulse is very similar in shape to the one in Fig. 1(a), with negligible dispersive broadening. Figure 2(a) gives the corresponding amplitude spectrum (medium-thick solid curve) that extends to approximately 3.5 THz. The clean pulse together with the smooth spectrum showing no cutoff is clear proof of single-TEM mode propagation. Single-TEM mode propagation was realized despite several higher-order modes (mentioned before) cutting in within the experimental bandwidth, signifying the excellent mode matching between the respective TEM modes in the AF and DF sections. This is believed to be the first demonstration of undistorted subpicosecond terahertz pulse propagation in a Si-filled PPWG.

In conclusion, a theoretical guided-wave model has been developed to describe the nature of terahertz pulse propagation in practical DF-PPWGs, which shows that submicrometer air gaps at the contact surfaces can have a dramatic effect on the propagation. Through the use of metallized dielectric surfaces, and a special air–dielectric–air waveguide geometry, undistorted terahertz pulse propagation via the single-TEM mode is demonstrated. These results will have important implications for future high-speed, integrated, guided-wave devices[4,6] that utilize PPWGs. Additionally, the strong field intensities in the air gaps of the DF-PPWG may prove it to be ideal for guided-wave terahertz spectroscopy of trace quantities filling the gaps.

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