

# Low-loss terahertz ribbon waveguides

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The submillimeter wave or terahertz (THz) band (1 mm–100  $\mu\text{m}$ ) is one of the last unexplored frontiers in the electromagnetic spectrum. A major stumbling block hampering instrument deployment in this frequency regime is the lack of a low-loss guiding structure equivalent to the optical fiber that is so prevalent at the visible wavelengths. The presence of strong inherent vibrational absorption bands in solids and the high skin-depth losses of conductors make the traditional microstripline circuits, conventional dielectric lines, or metallic waveguides, which are common at microwave frequencies, much too lossy to be used in the THz bands. Even the modern surface plasmon polariton waveguides are much too lossy for long-distance transmission in the THz bands. We describe a concept for overcoming this drawback and describe a new family of ultra-low-loss ribbon-based guide structures and matching components for propagating single-mode THz signals. For straight runs this ribbon-based waveguide can provide an attenuation constant that is more than 100 times less than that of a conventional dielectric or metallic waveguide. Problems dealing with efficient coupling of power into and out of the ribbon guide, achieving low-loss bends and branches, and forming THz circuit elements are discussed in detail. One notes that active circuit elements can be integrated directly onto the ribbon structure (when it is made with semiconductor material) and that the absence of metallic structures in the ribbon guide provides the possibility of high-power carrying capability. It thus appears that this ribbon-based dielectric waveguide and associated components can be used as fundamental building blocks for a new generation of ultra-high-speed electronic integrated circuits or THz interconnects. © 2005 Optical Society of America

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## 1. Introduction

There exists a frequency “gap” between 300 GHz and 10 THz that has not been significantly exploited due to a lack of both sources of submillimeter-wave power and an efficient low-loss circuit interconnect and guide structure.<sup>1–3</sup> The lack of an efficient low-loss circuit interconnect has limited both the complexity and the scale of THz components. It has meant that different components (sources, detectors, amplifiers, antennas, etc.) must either be placed in direct proximity to one another or they must be coupled by free space through bulky, fixed path, hard to align, and often lossy optical elements.<sup>3</sup> Even chip-to-chip interconnections at THz frequencies represent a serious problem at the present time.<sup>2</sup>

The realization of low-loss connections for electronic circuits operating in the frequency range from 300 GHz to 10 THz has been an unsolved problem for many years. Because of the presence of inherent vibrational absorption bands in solids, the elimination of impurities is no longer the solution for finding low-loss solids in this frequency range.<sup>4–10</sup> High skin-depth loss at these frequencies also eliminates the use of highly conducting materials to form metallic waveguides or coaxial lines.<sup>11</sup> It thus appears that continuously searching for ultra-low-loss solids or waveguide materials in this band is not likely to bear fruit.<sup>12,13</sup> Despite these formidable constraints, attempts have been made to transmit THz signals through oversized circular and/or rectangular metallic waveguides, through plastic ribbons with their associated high attenuation constants, and through the use of a surface plasmon polariton on a metallic wire with its obligatory high ohmic losses.<sup>14–18</sup> These guides cease to operate when path lengths of longer than a few centimeters are needed. In this paper we describe a way to guide THz signals with significantly lower loss. It is based on the use of specially designed low-loss dielectric ribbons that we discovered<sup>19</sup> with an attenuation constant that is as much as 100 times less than that of a conventional waveguide. The rib-

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bon can be made with selected high dielectric constant materials (e.g., alumina, silicon, InP, GaAs, etc.) and can be used as the fundamental building blocks for a new generation of ultra-high-speed electronic integrated circuits or THz interconnects.<sup>1-3</sup>

Here we describe the fundamentals of this family of fully functional ribbon-based low-loss THz guiding systems<sup>19-22</sup> including the analysis of an efficient input-output coupling mechanism, a design that achieves low-loss bends and branches, and a means of forming THz active circuit elements. Numerical simulation studies were carried out between 30 GHz and 3 THz. One notes that with the dielectric ribbon all dimensions scale with free-space wavelength  $\lambda_0$  and attenuation losses scale as  $\lambda_0^{-1}$ . The fact that active circuit elements may be integrated directly onto the planar ribbon structure and that the absence of metallic structures in the ribbon guide provides the possibility of high-power carrying capability should be noted. Just as the low-loss optical fiber has become the backbone of high-speed communication lines replacing copper-based transmission lines,<sup>4-10</sup> so may this low-loss dielectric ribbon circuit become the backbone of ultra-high-speed circuits replacing metal-based microstrip lines or waveguides.

## 2. Background

Because the ribbon concept that was discovered earlier<sup>19</sup> is not well known, we shall provide a brief description here. From the theory of wave propagation along a dielectric waveguide, the attenuation constant  $\alpha$  of a dielectric waveguide surrounded by dry air is given by the following formula<sup>19-22</sup>:

$$\alpha = \frac{8.686 \pi \epsilon_1 R \tan \delta_1}{\lambda_0}, \quad (1)$$

where the geometric loss factor is defined as  $\epsilon_1 R$ . It is given by

$$\epsilon_1 R = \frac{\epsilon_1 \int_{A_1} (\mathbf{E}_1 \cdot \mathbf{E}_1^*) dA}{(\mu/\epsilon)^{1/2} \left[ \int_{A_1} \mathbf{e}_z \cdot (\mathbf{E}_1 \times \mathbf{H}_1^*) dA + \int_{A_0} \mathbf{e}_z \cdot (\mathbf{E}_0 \times \mathbf{H}_0^*) dA \right]}. \quad (2)$$

Subscripts 1 and 0 denote quantities in the core and cladding regions, respectively. In Eq. (2),  $\epsilon_1$  and  $\tan \delta_1$  are the relative dielectric constant and the loss tangent of the dielectric core material, respectively,  $\mu$  and  $\epsilon_0$  are the permeability and permittivity of free space, respectively,  $\lambda_0$  is the free-space wavelength in meters, and  $\mathbf{e}_z$  is the unit vector in the direction of propagation.  $A_1$  and  $A_0$  are the cross-sectional areas of the core and the cladding region, respectively, and

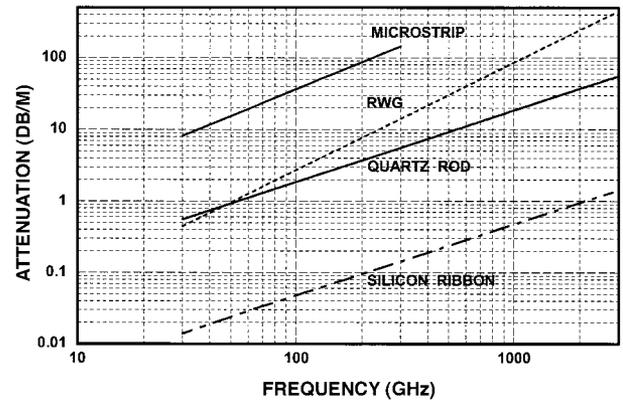


Fig. 1. Typical performance comparison between several conventional waveguide structures and the high dielectric constant (Si) ribbon waveguide for the frequency range from 30 GHz to 3 THz. Note that the waveguide losses of typical conventional waveguides can be as much as 100 times larger than those of the ribbon waveguide in this spectrum.

$(\mathbf{E}_1, \mathbf{H}_1)$  and  $(\mathbf{E}_0, \mathbf{H}_0)$  are the modal electric and magnetic field vectors of the guided mode in the core region and in the cladding region, respectively. Examination of the fundamental equation (1) governing the attenuation constant of a dominant mode guided by a simple solid dielectric waveguide surrounded by lossless dry air shows that the attenuation is dependent on the loss factor, the dielectric constant of the dielectric material, and the geometric shape of the guiding structure.<sup>19-22</sup> Since the material loss factor and the dielectric constant of a solid are fixed, the only way to reduce the attenuation constant is to find the most appropriate cross-sectional geometry of the waveguide. A systematic study on a variety of geometries shows that a ribbon-shaped guide made with a low-loss, high dielectric constant material, such as alumina, can yield an attenuation constant for the dominant TM-like mode of less than 0.005 dB/m in

the  $K_a$  band (28–40 GHz) (Ref. 19) and of less than 0.5 dB/m in the terahertz band (2–4 THz).

The significance of the development of the ribbon-based transmission system can be seen in Fig. 1. There the attenuation constant in dB/m is plotted as a function of operating frequency from 30 to 3000 GHz for several commonly used single-mode traditional waveguides and for the ribbon waveguide. These single-mode traditional waveguides are the

rectangular metallic waveguide, the circular dielectric guide with the same cross-sectional area as the dielectric ribbon, and the microstrip line. It is seen that at low frequencies (around 30 GHz), the rectangular metallic waveguide, quartz circular rod, and microstrip line are acceptable guides having attenuation constants ranging from 0.4 to 8 dB/m. The high loss of the microstrip line is tolerated since only short lengths are normally used. On the other hand, the silicon dielectric ribbon exhibits an attenuation constant of only 0.014 dB/m. As operating frequency  $f$  increases, attenuation also increases. For the rectangular metallic waveguide and the microstrip line, the attenuation increases at a rate proportional to approximately  $f^{3/2}$ . For the quartz circular rod and the silicon dielectric ribbon, it increases at a rate proportional to approximately  $f$ . At 300 GHz the attenuation for the microstrip line has reached approximately 150 dB/m (an onerous figure indeed), while that for the rectangular metallic waveguide is 15 dB/m and the quartz circular rod has a loss of 5.5 dB/m. At 300 GHz the attenuation for the silicon dielectric ribbon is approximately 0.15 dB/m, a figure significantly below that for the rectangular metallic waveguide at one tenth the frequency. At 3 THz the attenuation for the rectangular metallic waveguide has risen to more than 400 dB/m while that for the quartz circular rod has risen to more than 50 dB/m. These are extremely unattractive figures, rendering these waveguides impractical. Of course, the microstrip line is also impractical. It appears that the

only remaining candidate at 3 THz is the silicon or other low-loss high dielectric constant ribbon. There the attenuation for the ribbon is approximately 1.5 dB/m, which is a workable figure, and in fact the only viable guiding medium that has been proposed to date for cw THz signals.

Let us now turn to the important issues that involve utilizing the ribbon waveguide in actual circuits. These issues include how to transport THz signals around bends (corners) without excessive radiation loss, how to efficiently couple THz power to and from conventional waveguides and microstrip structures, and how to design specific circuit elements. Typical low-loss THz circuits or interconnects may contain not only the basic straight sections of low-loss dielectric ribbons but also the other necessary circuit components, such as couplers, bends and curves, branches and combiners, and filters. Many of these passive circuit components require a tightly confined mode. We will show that this is accomplished by using a polymer-coated high dielectric constant ribbon structure. Known numerical methods<sup>21–27</sup> will be used to analyze these components and to generate the desired results.

### 3. Ribbon Structures and Circuits

#### A. Polymer-Coated Alumina Ribbon Waveguide

From the discussion in Section 2, one expects that very low-loss guiding of terahertz band signals can be

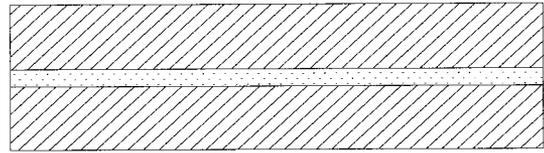


Fig. 2. Longitudinal cross-sectional geometry of a polymer-coated high dielectric constant ribbon. The thickness and the width of the high dielectric constant ribbon are, respectively, approximately  $0.0635 \lambda_0$  and  $0.635 \lambda_0$ . The thickness of the polymer coating is approximately  $0.25 \lambda_0$  and the width is approximately  $0.635 \lambda_0$ . The dielectric constant of the ribbon is 10 while that of the polymer is 2.04.

obtained with a ribbon-shaped guiding structure made with a moderately low-loss high dielectric constant material. However, since more than 90% of the guided power is carried in the lossless dry air region outside the ribbon structure, it is expected that a significant amount of guided power will be radiated and lost when the guiding structure encounters sharp curves or corners. To remedy this problem, a variant of the described ribbon guide is proposed wherein a thick polymer coating is added to the dielectric substrate in the vicinity of the bend or radiating region. A sketch of the structure is shown in Fig. 2. The polymer coating is introduced to provide tighter confinement of the guided power near the high dielectric constant ribbon. When a 10:1 aspect ratio, high dielectric constant ribbon ( $0.625 \lambda_0 \times 0.0625 \lambda_0$ ) is coated on both sides with a  $1/4 \lambda_0$  thick Teflon layer, more than 90% of the guided power for the dominant TM-like mode is contained within the boundary of the coated waveguide. This means that this coated ribbon can guide the dominant mode around corners, can divide or combine the power into or out of multiple waveguides, or can keep the mode confined in regions where radiation is likely. The calculated attenuation constant for the dominant TM-like mode in the Teflon-coated alumina ribbon is approximately 0.2 dB/mm at 3 THz (or 0.02 dB/free-space wavelength), an acceptable value for short-distance propagation. It thus appears that the Teflon-coated alumina ribbon can be used (with appropriate input-output matching) as an intermediate section for the design of all the components mentioned above. For long straight-run distances, a bare high dielectric constant ribbon with an attenuation constant of 0.0006 dB/mm at 3 THz should still be used.

A summary of the analyses and uses of the polymer-coated ribbon waveguide follows:

(a) The distribution of the guided power (Poynting's vector) for the dominant  ${}_{\text{e}}\text{HE}_{11}$  mode (TM-like mode) as a function of the distance away from the center major axis of the coated guide is shown in Fig. 3. Several cases with various Teflon-coating thicknesses are shown. It is seen that there exists a large discontinuity in the power distribution at the boundary between the low dielectric constant Teflon medium and the high dielectric constant alumina. The reason is that the normal displacement vector ( $D$ ) is

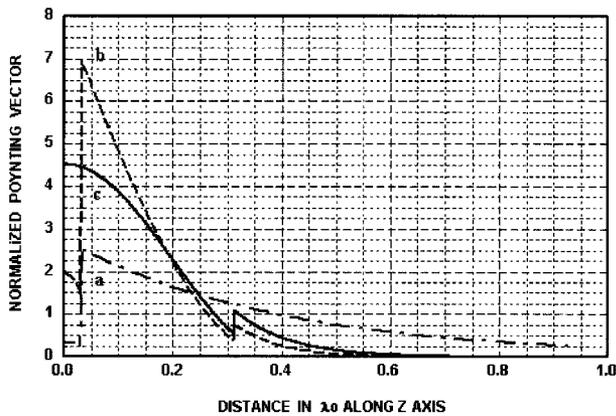


Fig. 3. Normalized power intensity in a polymer-coated high dielectric constant ribbon supporting the dominant TM-like mode. Three cases are shown. For case (a) the guiding structure is a bare  $0.635 \lambda_0$  (width)  $\times$   $0.06235 \lambda_0$  (height) high dielectric constant ribbon surrounded by dry air; for case (b) it is the same high dielectric constant ribbon coated on both (height) sides of the ribbon with a layer of Teflon  $0.25 \lambda_0$  thick; for case (c) it is a plain Teflon ribbon with dimensions of  $0.635 \lambda_0$  (width)  $\times$   $0.6235 \lambda_0$  (height) surrounded by dry air. Here  $\epsilon_2 = 2.06$  and  $\epsilon_1 = 10$  are, respectively, the dielectric constants of Teflon and high dielectric constant material, and  $\lambda_0$  is the free-space wavelength. The distributions of guided power for the three cases are as follows: For case (a) 1.04% is in the high dielectric constant material and 98.96% is in the air region; for case (b) 5.75% is in the high dielectric constant material, 87.8% is in the Teflon material, and 6.45% is in the air region; for case (c) 69.23% is in the Teflon material and 10.77% is in the air region. Note that for case (b) more than 93% of the guided power is contained within the coated waveguide structure.

continuous at the boundary and therefore the normal electric vector has a large discontinuity at the boundary when the dielectric constant differs greatly at the interface, resulting in a large discontinuity in the distribution of the Poynting's vector (power density) across the boundary. Specifically, the normal electric

vector undergoes a jump at the boundary that is equal to the ratio of the inner to outer relative dielectric constants of the two dielectrics involved. For the thin high dielectric constant ribbon case, the power density within the high dielectric constant region is quite small while the power density just outside the high dielectric constant boundary is very large. This distinctive hole-in-the-middle power distribution for this high dielectric constant ribbon must be considered in the design of an efficient coupler for this ribbon structure. When a thin layer (of around  $1/4 \lambda_0$ ) of the polymer is coated on the high dielectric constant ribbon, more than 90% of the guided power is contained within the coated guiding structure. This fact is very important because this means that this coated ribbon can turn corners without suffering significant radiation losses.

(b) A plot of the relative intensity envelope of the transverse  $E$  field in the upper half plane for a Teflon-coated high dielectric constant waveguide is shown in Fig. 4. The top row shows the cross-sectional view of the field and the bottom row shows the side view of the field distribution in the direction of propagation. The alumina is  $0.6 \lambda_0$  wide and  $0.06 \lambda_0$  thick. Three cases are considered: In case (a) there is no polymer coat; in case (b) the Teflon coat is  $0.1 \lambda_0$  thick; and in case (c) the Teflon coat is  $0.26 \lambda_0$  thick. Notice that the field is more confined to the structure for thicker coats. Most of the guided power is confined within the coated guiding structure when the Teflon thickness is about  $1/4 \lambda_0$ . When the thickness is reduced to zero, most of the power is confined within a distance of  $1 \lambda_0$  from the surface of the high dielectric constant ribbon in free space. Although there is a dip in the transverse field in the high dielectric constant material, the high dielectric constant ribbon is very thin and the dip may not be clearly seen in Fig. 4.

(c) Possible applications are as follows. A polymer-

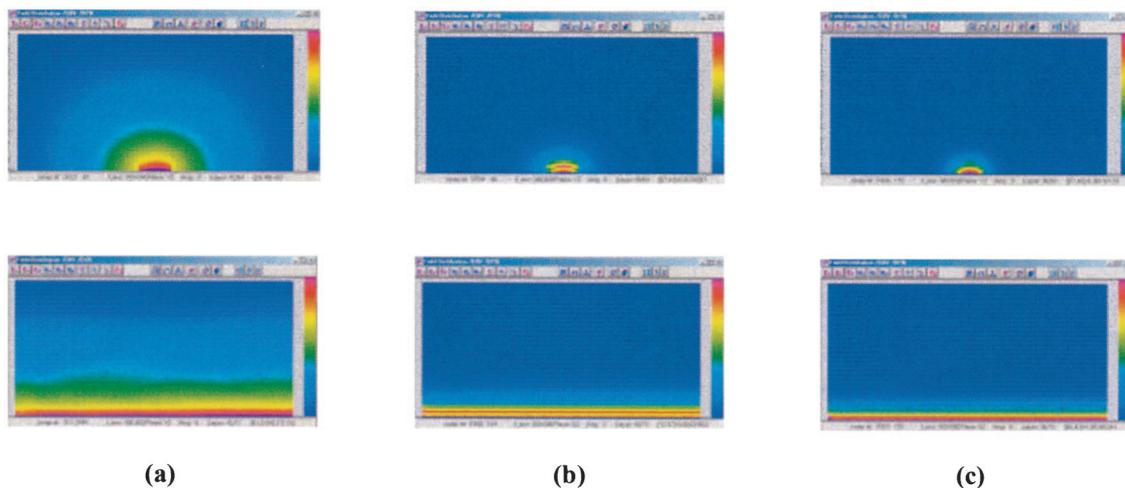


Fig. 4. Relative intensity (red is high and blue is low intensity) envelope of the transverse  $E$  field in the upper half plane for a Teflon-coated high dielectric constant waveguide. The top row shows the cross-sectional view of the field and the bottom row shows the side view of the field distribution in the direction of propagation. A sketch of the structure is shown in Fig. 2. The high dielectric constant ribbon is  $0.6 \lambda_0$  wide and  $0.06 \lambda_0$  thick. In (a) there is no polymer coat, in (b) the Teflon coat is  $0.1 \lambda_0$  thick, and in (c) the Teflon coat is  $0.26 \lambda_0$  thick. Note that the field is more confined to the structure for thicker coats.

coated high dielectric constant ribbon waveguide may be used: (1) as a transition region for (a) turning corners, (b) for making waveguide splits, (c) for shielding the guided wave from extraneous obstacles or interference, and (d) for providing efficient excitation of a desired mode. (Illustrative designs are given in the following sections); and (2) as a fundamental circuit element for designing low-pass, high-pass, or bandpass filters, couplers, patch antennas, array antenna elements, etc. Various high dielectric constant semiconductor materials such as GaAs, InP, or Si may be used to construct ribbon or polymer-coated ribbon waveguides. The additional advantage is that active elements may now be constructed from and/or on these ribbon or coated-ribbon waveguides, enabling the natural integration of passive and/or active elements and waveguiding structures. Such low-loss transmission media do not exist at this time for common commercial circuits at millimeter wavelengths, submillimeter wavelengths, or at THz frequencies. Components that would benefit from the use of Si, GaAsG, or InP ribbon waveguides include amplifiers, filters, up-down converters, oscillators, radiating antennas, phase shifters, millimeter wave monolithic integrated circuits (MMIC), or THz interconnects. As the frequency increases, the semiconductor-composed ribbon waveguide circuits become more desirable and can provide a whole new category of rf components and subsystems. They also solve major interconnect problems that now limit multichip MMICs at millimeter wavelengths.<sup>6,7</sup> Furthermore, they also provide high-power carrying capabilities.

#### B. Efficient Couplers for the Ribbon Waveguides

Three conditions must be satisfied to achieve efficient coupling of power into and out of a dielectric ribbon waveguide through the use of a transition.<sup>28</sup> (1) Impedance matching: The wave impedance of an incident wave (mode) must be as close as possible to that of the guided mode (TM-like mode) on the dielectric ribbon waveguide (Minimizing Fresnel loss belongs in this category.) This means that the transition between guides with highly dissimilar impedances must be very gradual. (2) Field matching: The transverse-field configuration (pattern) of the incident wave (mode) must be as close as possible to that of the guided mode (TM-like mode) on the dielectric ribbon waveguide. The presence of dissimilar transverse-field lines will induce radiated waves or higher-order modes. (3) Phase velocity matching: The phase velocity of the incident wave (mode) must be as close as possible to that of the guided mode (TM-like mode) on the dielectric ribbon waveguide. This means that the transition between guides with different phase velocities must be very gentle. It is perhaps worthwhile to mention that there exists another way of transferring power from one waveguide to another by the coupled-mode approach. According to the coupled-mode perturbation theory, power can be transferred from one guide to another if the modes on these guides possess a similar phase velocity and if

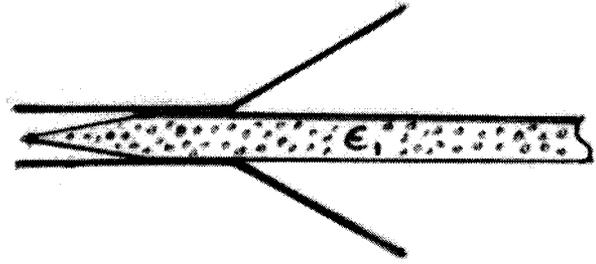


Fig. 5. Rectangular metal waveguide to low dielectric constant ribbon waveguide transition.

the proximity of the guides does not significantly affect the mode pattern of the guided wave on each guide. This concept has been used successfully to design traveling wave tubes, optical fiber couplers, and integrated optical planar waveguide couplers. The same concept can certainly be used here to design ribbon waveguide couplers.

#### 1. Transition between a Rectangular Metallic Waveguide and a High Dielectric Constant Ribbon Waveguide: Excitation of a Wave on a High Dielectric Constant Ribbon Guide

It is of paramount importance to be able to input power to the low-loss ribbon waveguide with a minimum of excitation loss to achieve an overall low-loss transport medium for terahertz signals. A conventional way of transferring power from a metallic waveguide to a low dielectric constant polymer waveguide is by use of a transition horn.<sup>28</sup> The cross-sectional size of the polymer guide is normally larger than that of the metallic waveguide. To provide a good impedance match and a good field pattern match, the polymer dielectric waveguide is inserted into the metallic waveguide, fully filling its cross section, and the inserted end of the polymer guide is gently tapered to a point. Most of the guided power is already contained within the polymer at the mouth of the metallic waveguide. Mismatching of the transverse field for the polymer-filled metallic waveguide and that of the polymer dielectric waveguide will excite a radiated wave, which will detract from the guided power. To remedy this situation a metallic transition horn is placed at the end of the polymer-filled metallic waveguide (Fig. 5). In this way a very gentle transition of the field inside the polymer-filled metallic waveguide to that of the pure polymer waveguide occurs. The guided power inside a polymer-filled metallic waveguide is fully launched onto the polymer guide, generating very little lost radiated power. A coupling efficiency of as high as 98% has been achieved.<sup>28</sup>

The situation is quite different for making a transition from a rectangular metallic waveguide to a high dielectric constant ribbon guide. Two salient features stand out: (1) The transverse electric field pattern for the ribbon guide has a significant dip inside the high dielectric constant ribbon while that for the rectangular metallic waveguide does not. (2) Due to the severe discontinuity of the transverse

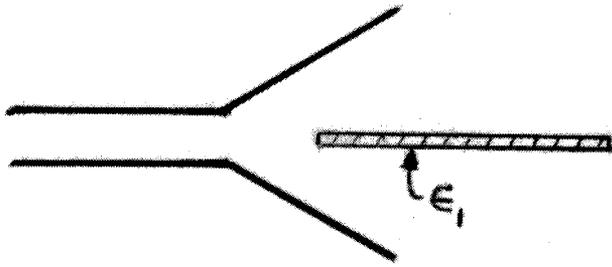


Fig. 6. Rectangular metal waveguide to high dielectric constant ribbon waveguide transition.

electric field at the surface of a high dielectric constant ribbon, tapering the thickness of the ribbon can cause significant perturbation to the guided wave, thus producing a large radiation loss. This means that the conventional way of making the transition for a rectangular metallic waveguide to a polymer dielectric waveguide cannot be used for the high dielectric constant ribbon guide. Here, to minimize impedance mismatch, the high dielectric constant ribbon should not be inserted into the metallic rectangular waveguide. Instead it will be placed partially into the mouth of the horn and only its width will be tapered in the transition region. (See Fig. 6.) Note that tapering the width of the ribbon would not cause a large disturbance to the transverse electric field due to the tangential field continuity condition. Despite the field mismatch in the region inside the high dielectric constant ribbon, strong coupling of the electric field on the surface of the high dielectric constant ribbon with the relatively uniform transverse electric field of the horn and good matching of the phase velocity for these fields can provide an excellent condition for the efficient launching of the desired guided wave on the high dielectric constant ribbon guide. Using this transition method a measured value of 0.35 dB mismatch loss was attained at the  $K_a$  band.<sup>19</sup>

## 2. Transition between the High Dielectric Constant Ribbon Waveguide and the Strongly Guided Polymer-Coated High Dielectric Constant Ribbon Waveguide

To show the compatibility between the high dielectric constant ribbon and the (low dielectric constant) polymer-coated high dielectric constant ribbon, we have studied the transition problem involving these structures. The transition from the

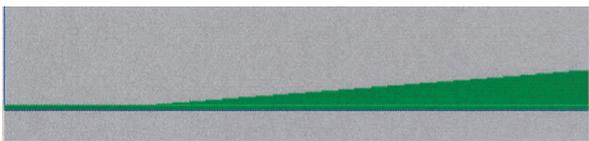


Fig. 7. Side view of the top half of transitions from a high dielectric constant ribbon to a polymer-coated high dielectric constant ribbon using a gradual taper. The high dielectric constant ribbon is  $0.6 \lambda_0$  wide and  $0.06 \lambda_0$  thick. The polymer is Teflon ( $0.6 \lambda_0$  wide and  $0.26 \lambda_0$  thick). The transition length is  $6 \lambda_0$ .

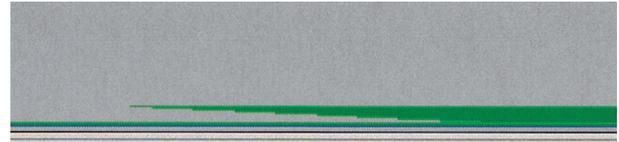


Fig. 8. Side view of the top half of transitions from a high dielectric constant ribbon to a polymer-coated high dielectric constant ribbon using an inverse taper. The high dielectric constant ribbon is  $0.6 \lambda_0$  wide and  $0.06 \lambda_0$  thick. The polymer is Teflon ( $0.6 \lambda_0$  wide) and the final coating is  $0.26 \lambda_0$  thick. The transition length is  $6 \lambda_0$ .

low-loss high dielectric constant ribbon to a tightly guided polymer-coated high dielectric constant ribbon can be accomplished by tapering the polymer coating. Two types of tapering have been studied: the first is to linearly taper the polymer thickness from the surface of the high dielectric constant ribbon to the desired coating thickness (Fig. 7), and the second type of tapering is done by inverting the first linear taper (Fig. 8). Both tapering sections are  $6 \lambda_0$  long. Figure 8 shows a sketch of a new transition section that will gently capture and guide the surface wave on the high dielectric constant ribbon and couple it into the strongly guided polymer-coated ribbon. Since the key to avoiding the generation of a radiated wave is to perturb the guided field as little as possible, the transition (an inverted polymer dielectric taper) is initiated in a region of weak field strength. Its influence is gradually increased through the thickening of the polymer layer, eventually reaching the desired coating thickness. Computer simulations using the finite-difference time domain (FDTD) program<sup>27</sup> illustrate how the incident guided wave evolves as it propagates through this tapered transition (Figs. 9 and 10). The numerical results show that the insertion loss for the first linear taper is 0.3 dB while that for the second inverted taper is 0.22 dB. These are acceptable figures if only a couple of transition regions occur along the guide, indicating good compatibility between the high dielectric constant ribbon and the Teflon-coated high dielectric constant ribbon. According to the reciprocity theorem, the insertion loss for the inverse taper (polymer coated to uncoated ribbon) should be identical. Lower-loss transitions, including step-compensated versions, are under investigation.

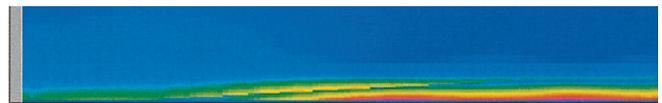


Fig. 9. For the structure shown in Fig. 7 the FDTD simulation is obtained at 3 THz for the envelope of the transverse  $E$  field of the TM-like mode, which propagates from the bare high dielectric constant ribbon through the transition to the coated high dielectric constant waveguide. The direction of propagation is to the right. The color intensity scale shows the relative intensity of the transverse field at the center of the guide. The insertion loss of this transition is 0.3 dB.



Fig. 10. For the structure shown in Fig. 9, the FDTD simulation is obtained at 3 THz for the envelope of the transverse  $E$  field of the TM-like mode that propagates from the bare high dielectric constant ribbon through the transition to the coated high dielectric constant waveguide. The direction of propagation is to the right. The color intensity scale shows the relative intensity of the transverse field at the center of the ribbon guide. The insertion loss of this transition is 0.22 dB.

### 3. Step-Index Transition from High Dielectric Constant Ribbon to Polymer-Coated High Dielectric Constant Ribbon

Strictly speaking, a step-index transition is a discontinuity, not a transition. It is nevertheless an important circuit element because it can be used to design filters for the ribbon-based circuits provided that radiation loss is not excessive.<sup>12,13</sup> A picture of a step-index transition is shown in Fig. 11(a). Figure 11(b) shows the envelope of the  $E$  field perpendicular to the ribbon surface as the guided wave propagates through this transition from a bare high dielectric constant ribbon to a polymer-coated high dielectric constant ribbon and back to a bare high dielectric constant ribbon. A standing wave is clearly seen at the input end of this transition. Although a significant reflective component is evident, it is encouraging to note from the  $S$  parameter<sup>11–13,20</sup> calculation that the radiation loss is not excessive. The insertion radiation loss is approximately 0.5 dB. Therefore, the step index can be used as a circuit component, as in a filter design.<sup>12,13</sup> Note that this design is limited to single-mode waveguides. Al-

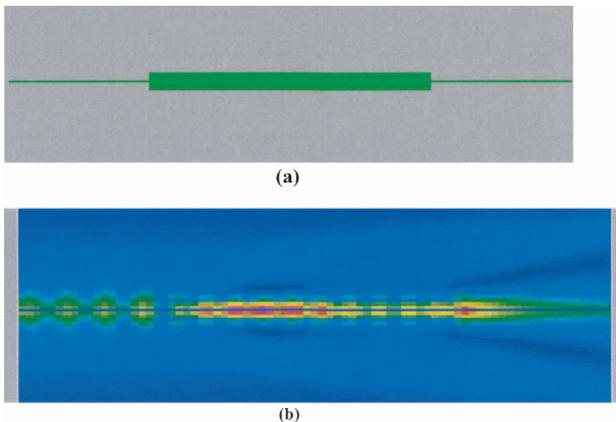


Fig. 11. (a) Side view sketch of a step-index transition from high dielectric constant ribbon to a polymer-coated high dielectric constant ribbon. The high dielectric constant ribbon is  $0.6 \lambda_0$  wide and  $0.06 \lambda_0$  thick. The top and bottom polymer coats are each  $0.6 \lambda_0$  wide and  $0.26 \lambda_0$  thick. (b) Side view of the envelope of the transverse  $E$  field for the TM-like mode propagating through the structure shown in (a). The polymer is Teflon. The simulation at 3 THz shows that for this step-index transition there is significant reflection but little radiation loss. This means that the step-index transition can be used to design circuits, such as filters, on the high dielectric constant ribbon waveguide. The insertion radiation loss is around 0.5 dB.

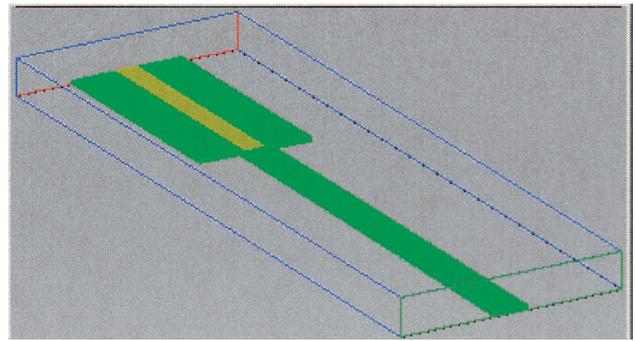


Fig. 12. Sketch of the butt-jointed transition from microstrip line to polymer-coated high dielectric constant waveguide on a ground plane.

though the ribbon structure and the polymer-coated ribbon structure are operating in the single-mode region, these are still open surface-wave structures, implying the possible presence of a radiated wave. Therefore, limiting the excitation of the radiated wave is necessary to ensure the successful application of this design approach.

The combination of the transition section with the polymer-coated high dielectric constant guide having a highly confined field can be used to build other components such as power splitters and combiners, waveguide twists, couplers, isolators, or Faraday rotators. The waveguide structure can be supported by ultrathin dielectric wires (as long as their diameter is small compared to a wavelength) without any significant added losses.

### 4. Transition between Microstrip Line and High Dielectric Constant Ribbon

Microstrip lines of several forms (strip line, coplanar waveguide, microstrip, etc.) have been the backbone for wave propagation on planar microwave circuits for many decades. Despite their high-loss characteristics at submillimeter wavelengths, they are still being used due to a lack of alternative structures. To couple the available microstrip line geometries with the new low-loss ribbon structures, it is important to find an efficient and readily fabricated transition. For interchip or off-chip use the simplest transition is to directly “butt-joint” the microstrip line with the ribbon waveguide. Because of inherent mismatches, this gives an unacceptable mismatch. However, if a butt joint is made between the microstrip and a polymer-coated ribbon the situation is not nearly as bad. A sketch of such a transition (for analysis purposes) is shown in Fig. 12. Most of the transverse electric field for the microstrip is confined between its top conductor and its bottom conducting ground plane, and for the polymer-coated alumina ribbon over a ground plane the transverse electric field of the dominant mode is mostly confined within the polymer layer. The similarity of these transverse electric field patterns enables one to butt-joint the polymer microstrip line to the polymer-coated high dielectric constant ribbon on a ground plane and to expect excellent field

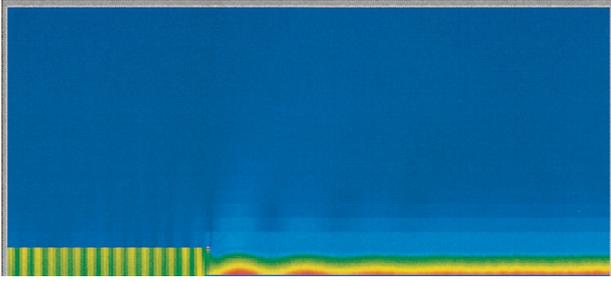


Fig. 13. Side view of the envelope of the transverse  $E$  field for the TM-like mode propagating through the structure shown in Fig. 12. The microstrip line structure is on the left with a  $0.22 \lambda_0$  thick polyethylene substrate on a ground plane and a  $0.32 \lambda_0$  wide metal microstrip line conductor. The polymer-coated high dielectric constant ribbon waveguide is on the right, where the ribbon is  $0.6 \lambda_0$  wide, the high dielectric constant material is  $0.03 \lambda_0$  thick, and the polymer coat is polyethylene ( $0.2 \lambda_0$  thick) on top of the high dielectric constant material, also placed on the ground plane. The microstrip line is  $4 \lambda_0$  long and the coated polymer ribbon is  $8 \lambda_0$  long. The transmission loss from left to right is 0.35 dB.

matching for a low-loss transition. In this simulation a polyethylene substrate is used in the microstrip line and a polyethylene coating is used on the high dielectric constant ribbon. These dielectrics were chosen to get a closer impedance and phase velocity match. Computer simulation of the envelope of the transverse  $E$  field as it propagates from the microstrip line into the polymer-coated high dielectric constant ribbon is shown in Fig. 13. A slight standing-wave pattern is seen in the simulation. This can be further reduced by optimizing the structural dimensions. A total loss (reflection and radiation) of 0.24 dB was found for this transition.

If the microstrip line dielectric is made with a high dielectric constant material rather than with polyethylene, the simple butt-joint technique does not work well. There is a now substantial difference between the transverse electric field for the microstrip and that for the high dielectric constant ribbon: The highest concentration of the transverse electric field resides in the high dielectric constant substrate between the conducting surfaces of the microstrip line while the highest field concentration resides just outside the surface of the high dielectric constant ribbon with a substantial dip inside the high dielectric constant material. It is therefore prudent not to butt-joint the two ends of these different waveguides. In this situation an additional transition section must be employed. From the experimental results at the  $K_a$  band using an alumina (high dielectric constant) ribbon partially inserted into a horn, the following microstrip line-to-coated high dielectric constant ribbon can be envisioned. One must first transform the high concentration of the transverse electric field inside the high dielectric constant substrate of the microstrip line to a transverse field confined between two conducting planes filled with air. Tapering the width of the high dielectric constant substrate to a sharp edge and simultaneously widening the upper conducting microstrip line accom-

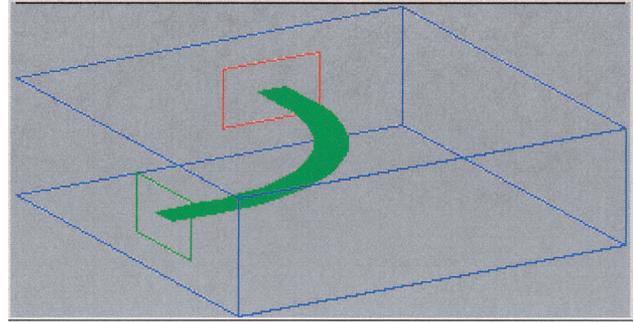


Fig. 14. A  $90^\circ$  alumina ribbon bend. The ribbon is  $0.6 \lambda_0$  wide with a  $1 \lambda_0$  input and output straight section and a  $4 \lambda_0$  inside radius bend.

plishes this. This section of the transition basically transforms the high dielectric constant material-filled microstrip line to an air-filled parallel-plate transmission line. The upper and lower plates of this transmission line are flared into a horn structure. The high dielectric constant ribbon is then inserted part of the way into this flared region to accommodate efficient transfer of the guided wave. It should be noted that, since the metal surface forms an integral part of microstrip line and since the loss for metallic material increases dramatically as operating frequency increases, the above transition consideration is only meaningful for frequencies of much less than 100 GHz and not for the THz band. Further investigation of this problem is in progress.

### C. Bends and Corners

Since the highest concentration of guided field resides just outside and near the surface of the high dielectric constant ribbon waveguide, the ribbon waveguide is a true surface waveguide. As such the external field can easily “slide” off the guiding structure and transform into the radiated field when the ribbon guide bends (Fig. 14). This is clearly seen in Fig. 15 where the behavior of the dominant electric field is plotted as the ribbon guide turns a  $90^\circ$  corner with a radius of curvature of  $4 \lambda_0$ . Almost all of the guided field is radiated. To develop a low-loss bend, it is necessary first to transition the surface-guided, low-loss high dielectric constant ribbon to the strongly guided

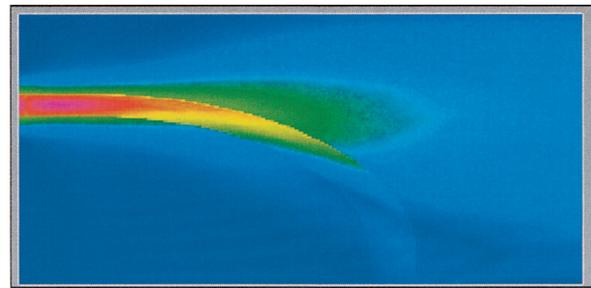


Fig. 15. Top view of the envelope of the transverse  $E$  field for the TM-like mode, just outside the high dielectric constant ribbon, as it propagates around the bend shown in Fig. 14. Almost all of the initial guided wave is lost to radiation.

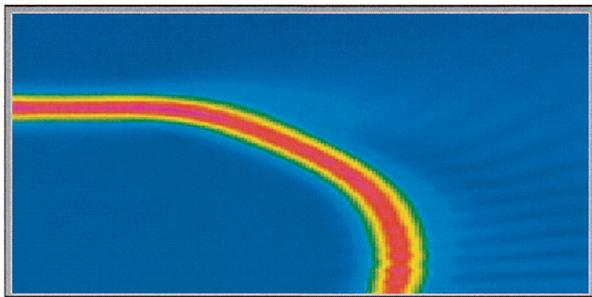


Fig. 16. Top view of the envelope of the transverse  $E$  field for the TM-like mode, just inside the Teflon-air boundary, for the high dielectric constant ribbon bend shown in Fig. 12 with a Teflon coat ( $0.26 \lambda_0$  thick) on either side of the alumina. Almost all of the initial guided wave is transmitted through the bend. The radiation loss is less than 0.1 dB.

polymer-coated high dielectric constant ribbon that was discussed earlier. Basically the low-loss bends are bends using a polymer-coated high dielectric constant ribbon waveguide. Computer simulation of the guided field around a  $90^\circ$  bend having a radius of curvature of  $4 \lambda_0$  on the polymer-coated ribbon was carried out. This is displayed in Fig. 16. It is seen that since most of the guided field is already confined within the polymer-coated guide prior to turning the corner, very little guided field is transformed into a radiated field when the polymer-coated guide turns a corner. The total  $90^\circ$  cornering loss is found to be less than 0.2 dB.

#### 4. Conclusion

We have shown how the lack of a viable low-loss transmission system in the THz spectrum may be overcome with the use of newly developed ribbon-based waveguides<sup>19</sup> and transitions. The propensity of the field to lie outside the guide substrate was shown to be problematic due to loose fundamental mode coupling and hence increased radiation around bends, transitions, or discontinuities. This problem has been overcome by adding a low dielectric constant polymer coating to the top and bottom of the ribbon guide in the immediate vicinity of the radiating regions. The extra dielectric loss introduced by the coating is minimized by keeping the coated length short ( $<10$  wavelengths). Several new transitions into and out of the coated and uncoated ribbon guide were proposed and analyzed. These gave mismatch losses below 0.25 dB per transition, which is acceptable for small numbers of transition regions within a circuit. Lower-loss transitions are being investigated for more complex circuits that might contain many discontinuous regions. The same polymer-coated ribbon structures that are used to confine the dominant mode around bends can be used to make low-loss transitions into and out of a low dielectric constant microstrip line or can be used as filter elements on a straight ribbon guide. Plans for realizing a ribbon guide at THz frequencies are ongoing, with silicon being one of the materials of choice for operation at these wavelengths. Although this paper presents the

basis and first realization to our knowledge of ribbon guide circuit elements for terahertz applications, there are still material and construction issues that must be solved before these components can find their way into practical circuits. One of the first applications is to build flexible sensor and/or source heads for some of the terahertz imaging instruments that are beginning to emerge.<sup>29</sup> At this time to our knowledge no other low-loss guide media exists at these wavelengths. We hope that the concepts presented here will lead to many more component and transition realizations and to practical use of the ribbon guide in the near future.

Just as the low-loss optical fiber has become the backbone of high-speed communication links, replacing copper-based transmission lines, we hope that the low-loss dielectric ribbon guide can become the backbone of ultra-high-speed circuits, replacing metal-based microstrip lines or waveguides. Armed with this low-loss THz interconnect media, one may find applications in medical diagnostics, radar, mechanically flexible sensors and sources, short- or long-distance communication links, MMIC interconnects, and perhaps even in micromachined on-chip transmission-line networks for ultrafast computers and/or processors.

#### 5. Appendix A: Comments on the Use of Pure Numerical Methods

The power of using a pure numerical approach in solving many problems that cannot be solved by analytical means is apparent. Nevertheless, it must be noted that results obtained by numerical techniques are only as good as the understanding of the problem that is usually guided by the analytic solution of a canonical problem. Here the canonical problem is wave propagation on an elliptical dielectric waveguide, which was solved many years ago by Yeh.<sup>21,22</sup> Associated with this problem is the problem of wave propagation on a circular dielectric waveguide, which was solved even earlier by Carson, *et al.*<sup>30</sup> Some of the major findings that are applicable to the ribbon waveguide are as follows<sup>21,22</sup>:

- (a) Only hybrid modes containing all six field components can exist on an elliptical dielectric waveguide or on an alumina ribbon waveguide.
- (b) The dominant modes are also hybrid modes, one with its dominant electric field parallel to the major axis of the ribbon and one with its dominant electric field parallel to the minor axis of the ribbon.
- (c) No evanescent mode can exist on the ribbon waveguide. Below the cutoff of a higher-order mode, that mode simply no longer exists.
- (d) Unless the excitation field matches exactly the total modal field of modes that can exist on the dielectric structure, unguided radiation fields will be launched and lost.
- (e) Any disturbance or deviation (such as curves, bending, twisting, narrowing or broadening, blemishes, etc.) that occurs to a perfectly straight dielectric structure will generate radiated waves and/or

other higher-order guided waves if they can exist on this structure. No evanescent modes are generated because they do not exist on a dielectric waveguide.

(f) Characteristic impedance for a given propagating mode used in transmission lines, microstrip lines, or metallic waveguides is usually defined as the ratio of the transverse electric field to the transverse magnetic field of that mode.<sup>12,13,21,22</sup> When this definition is used for the hybrid mode on an elliptical or ribbon dielectric waveguide, the characteristic impedance becomes dependent on the transverse spatial coordinates of the ribbon. In the traditional microwave circuit design, the characteristic impedance of a transmission circuit must have a value that is independent of any spatial coordinates.<sup>11,12,20–22</sup> This ambiguity must be resolved before the conventional circuit techniques can be used to analyze the ribbon waveguides based on the conventional transmission-line theory.

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