Bends in Nonradiative Dielectric Waveguides

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Abstract —**An experimental study was made of bends in the nonradiative dielectric waveguide (NRD-guide) at 50 GHz. The main cause of the bending losses was found to be due to the reflection at the transitions between the straight and curved waveguides rather than due to the radiation. The width of the dielectric strip was experimentally optimized in order to reduce the reflection, and a bend with a curvature radius as small as one guide wavelength could be realized.**

The experimental results are examined theoretically. The theory implies that the NRD-guide has a favorable tendency to suppress not only the radiation but also the reflection at the curved sections. It is also shown that the field maximum moves outwards or inwards from the mean path of the curved guide according to whether the dielectric strip is wider or narrower than a certain critical width. This critical width can be adopted as a design criterion for a low loss, very sharp NRD-guide bend.

I. INTRODUCTION

ALTHOUGH TRANSMISSION losses of dielectric waveguides are reasonably small along the straight sections, radiation losses at the bends are often formidable. Reducing the radiation losses is an urgent need when using dielectric waveguides in millimeter-wave integrated circuits. Use of the trapped image guide [1] is one possible candidate for this purpose and the nonradiative dielectric waveguide (NRD-guide) [2], [3] is another which has been proposed as a radiation free dielectric waveguide.

The NRD-guide resembles the *H*-guide [4] in structure, except that the sidewall separation is smaller than half a wavelength. Since the electric field is parallel to the metal plates, radiation, if any, is suppressed due to the cutoff property of the sidewalls. In order to confirm applicability of the NRD-guide in millimeter-wave integrated circuits, an experimental study was made of 90° and 180° bends at 50 GHz.

Measurements showed that the NRD-guide can almost completely suppress the radiation at the bends as expected, so that a minimum radius of bending is determined by the reflection rather than the radiation. The width of the strip was experimentally optimized in order to reduce the reflection at the bends, and a bend of a curvature radius as small as one guide wavelength could be fabricated.

An analysis is also made based on the WKB approximation. One of the results which the theory predicts is that the field maximum moves outwards or inwards from the mean path of the curved guide depending on whether the dielectric strip is wider or narrower than a certain critical width. Such an inward shift of the dominant mode field maximum is peculiar to the NRD-guide, and the critical width can be accepted as a criterion for designing a low loss, very sharp bend. The field profile, the shift of the field maximum, and the propagation constant in the curved NRD-guide are calculated.

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II. MEASUREMENTS OF BENDING LOSSES

Before going into the main subject, it will be helpful to see what the dominant mode in the NRD-guide looks like. Though it is a hybrid mode, the field lines in a transverse plane are very similar to those in a rectangular metal waveguide, except for evanescent fringes near the air–dielectric interfaces. For reference, there is a rough sketch of the field lines of the dominant mode in Fig. 1.

Fig. 2 is a cutaway view of an NRD-guide 90° bend. Polystyrene ($\epsilon_r = 2.56$) was chosen as strip material because of its good machinability, and brass plates were used as the sidewalls. The dielectric strips used here were 2.7 mm in height (a) and 2.4 mm in width (b). The radius of bending was varied as $R = 20$ mm, 16 mm, 12 mm, 10 mm, and 8 mm, and the width of the dielectric strip (b_c) at the curved sections was made equal to or smaller than the normal width (b) by the reason explained later. A taper about 15 mm in length, when necessary, was provided to realize a smooth transition between the straight guide and the bend of the reduced width. The bending losses were measured by the substitution method using a straight strip equal in length to the bend as the standard of comparison to remove the effect of the transmission losses. Since a 50-GHz sweeper was not available, a klystron oscillator was used in a manual tuning operation. This handicap somewhat reduced the accuracy of the measurements.

Fig. 3 shows the results of loss measurements for the case of $R = 20$ mm. The bending losses are negligible. This is surprising considering the large amount of radiation which might be caused at a bend of such a small curvature radius in an image guide [5]. This fact emphasizes the advantage of using the NRD-guide in millimeter-wave integrated circuits.

The bending losses for the case of $R = 16$ mm are shown in Fig. 4(a). Several peaks appeared in the loss curve. These peaks may be attributed to reflection rather than radiation. Among several ways tried for eliminating the reflection, narrowing the strip at the bend was found to be most effective. In fact, the reflection peaks disappeared as shown

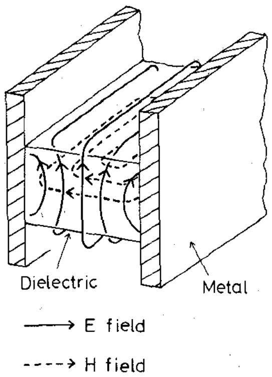

Fig. 1. Rough sketch of field lines in the NRD-guide.

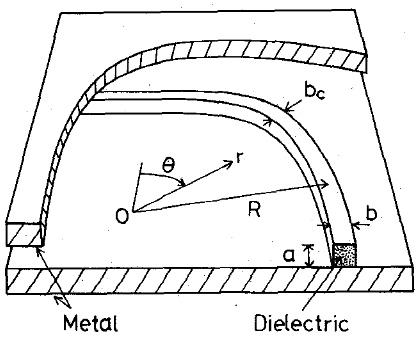

Fig. 2. Bend in the NRD-guide. R is the bending radius. a and b are height and width of a dielectric strip along the straight section, and b_c is width of the strip at the bend.

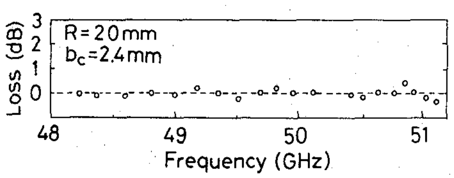

Fig. 3. Bending losses of a 90° bend ($R = 20$ mm).

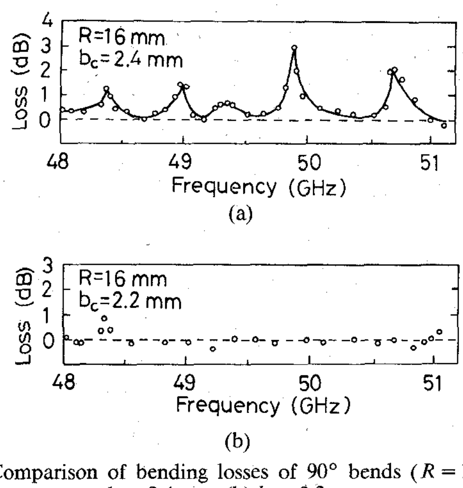

Fig. 4. Comparison of bending losses of 90° bends ($R = 16$ mm). (a) $b_c = 2.4$ mm. (b) $b_c = 2.2$ mm.

in Fig. 4(b) with a reduction in the width of the strip by 0.2 mm along the curved section. This is in contrast to the image guide, in which the bending losses increase due to the increase in the radiation, if the strip is narrowed at the bend. A theoretical explanation for this reduction of the reflection will be given in the next section.

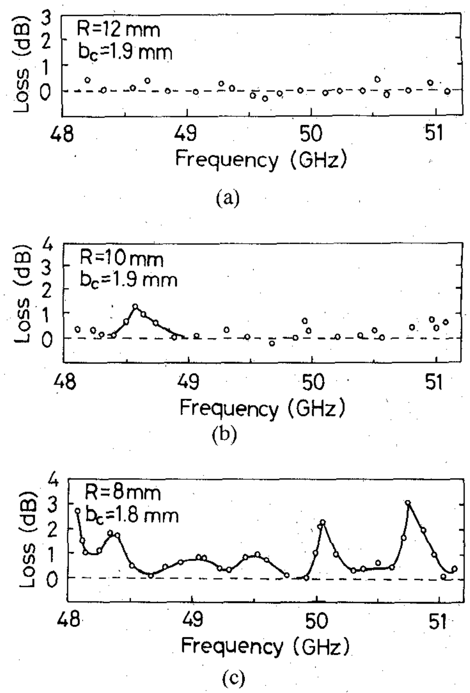

Fig. 5. Comparison of bending losses of 90° bends. (a) $R = 12$ mm and $b_c = 1.9$ mm. (b) $R = 10$ mm and $b_c = 1.9$ mm. (c) $R = 8$ mm and $b_c = 1.8$ mm.

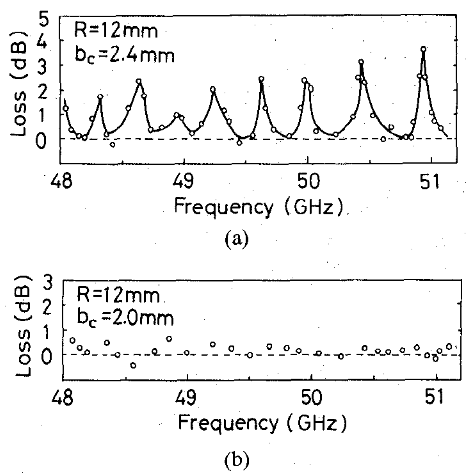

Fig. 6. Comparison of bending losses of 180° bends ($R = 12$ mm). (a) $b_c = 2.4$ mm. (b) $b_c = 2.0$ mm.

Further results for smaller values of R with reduced widths of strips are presented in Fig. 5. The bending losses are almost eliminated in Fig. 5(a) and (b), but in the case of $R = 8$ mm in Fig. 5(c), the reflection still remains even if the strip is narrowed to 1.8 mm. Further reduction of the strip width might eliminate the remaining reflection, but it is not practical since the operational bandwidth of the bend considerably decreases as the strip narrows. Taking this into consideration, it may be said that a practical minimum radius of bending is somewhat larger than 8 mm or, in other words, it is about one guide wavelength, that is, 8.7 mm in the present case.

Very similar results were obtained for 180° bends. As an example, the case of $R = 12$ mm is shown in Fig. 6. Comparing Fig. 6(a) and (b) reveals that narrowing the strip is still valid for the 180° bends.

III. Analysis of Bends in NRD-Guide

A. Derivation of Field Expressions

Bends in the NRD-guide will be treated theoretically in this section. The analysis starts with the well-known transformation [6]

$$w = R\ln(r/R) \tag{1a}$$

$$z = R\theta \tag{1b}$$

where R is the mean radius of bending, and r and θ are the cylindrical coordinates shown in Fig. 2. The wave equation for the curved guides can be written in the (w, z) plane as

$$\frac{\partial^2\psi}{\partial^2 w}+\frac{\partial^2\psi}{\partial^2 z}+k_0^2\left[\epsilon-\left(\frac{\lambda_0}{2a}\right)^2\right]\exp\left(\frac{2w}{R}\right)\psi=0 \tag{2}$$

where ψ can be any one of the rectangular field components, a is the sidewall separation of the NRD-guide, k_0 is the free-space wavenumber, $\lambda_0(=2\pi/k_0)$ is the free-space wavelength, and ϵ is the relative dielectric constant of the media which is ϵ_r in the dielectric strip and unity in the surrounding air.

The effective dielectric constant

$$\epsilon_e=\left[\epsilon-\left(\frac{\lambda_0}{2a}\right)^2\right]\exp\left(\frac{2w}{R}\right) \tag{3}$$

is plotted in Fig. 7 for a typical case. Since the effective dielectric constant is always negative outside the dielectric core region, electromagnetic tunnelling [7] never occurs, and hence there is no radiation at all at the bends. Therefore, it may be said again that the bending losses in the NRD-guide are due to the reflection at the transitions between the straight and curved guides.

The WKB-approximation can be used to solve (2) under certain restrictions which are satisfied in the present case. The formal solution is obtained in the following form:

$$\psi = Ar^{-1/2}p(r)^{-1/4}\exp\left[-\int_{R+b_c/2}^{r}p(r)^{1/2}\,dr\right],\qquad R+\frac{b_c}{2}<r \tag{4a}$$

$$\psi = Br^{-1/2}q(r)^{-1/4}\cos\left[\int_{R-b_c/2}^{r}q(r)^{1/2}\,dr+\delta\right],\qquad R-\frac{b_c}{2}<r<R+\frac{b_c}{2} \tag{4b}$$

$$\psi = Cr^{-1/2}p(r)^{-1/4}\exp\left[-\int_{r}^{R-b_c/2}p(r)^{1/2}\,dr\right],\qquad r<R-\frac{b_c}{2}, \tag{4c}$$

where

$$p(r)=\left[\left(\frac{\pi}{a}\right)^2-k_0^2+\left(\frac{\beta_c R}{r}\right)^2\right] \tag{5a}$$

$$q(r)=\left[\epsilon_r k_0^2-\left(\frac{\pi}{a}\right)^2-\left(\frac{\beta_c R}{r}\right)^2\right]. \tag{5b}$$

In the above equations, β_c, δ, and the ratios A/B and C/B are unknowns to be determined and β_c, in particular, can be interpreted as the propagation constant along the mean path of the bend.

To be more specific, let ψ be the component of the magnetic field normal to the sidewalls (see Fig. 1); then the field expressions are completely determined by requiring the continuity of

$$\psi \quad\text{and}\quad \frac{1}{\epsilon}\frac{\partial\psi}{\partial r}$$

across the air–dielectric interfaces. Numerical calculation is made of the field profile, the shift of the field maximum, and the propagation constant in the curved NRD-guide. But, since the theory is not so general as to explain the measurements consistently, only qualitative discussions and inferences are made within a somewhat limited scope in the next section. The mode conversion or other effects has to be taken into account to further understand the bends as is done for optical fibers [9].

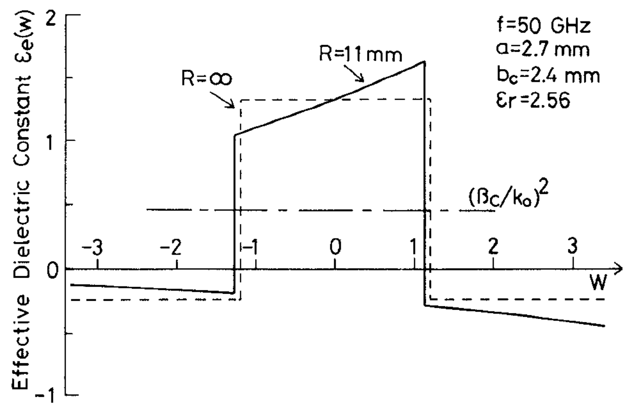

Fig. 7. Transverse profile of the effective dielectric constant in the curved NRD-guide.

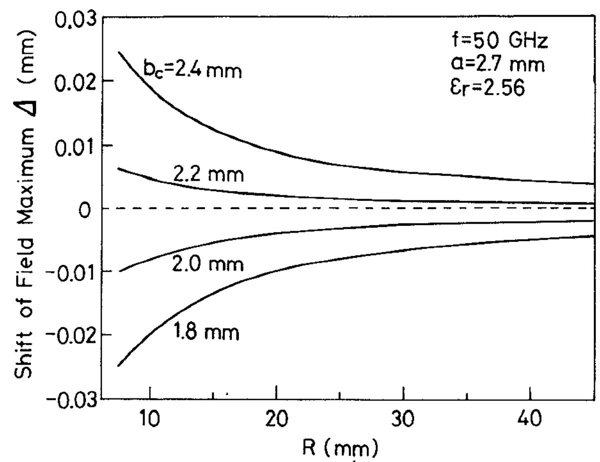

Fig. 8. Shift of the field maximum from the mean path of the curved NRD-guide as a function of the bending radius.

B. Numerical Calculation and Discussions

First of all, the shift of the field maximum Δ is calculated for the polystyrene strip at 50 GHz and plotted in Fig. 8 as a function of the bending radius. The positive values are for the outward shifts from the mean path of the curved guide, while the negative values are for the inward

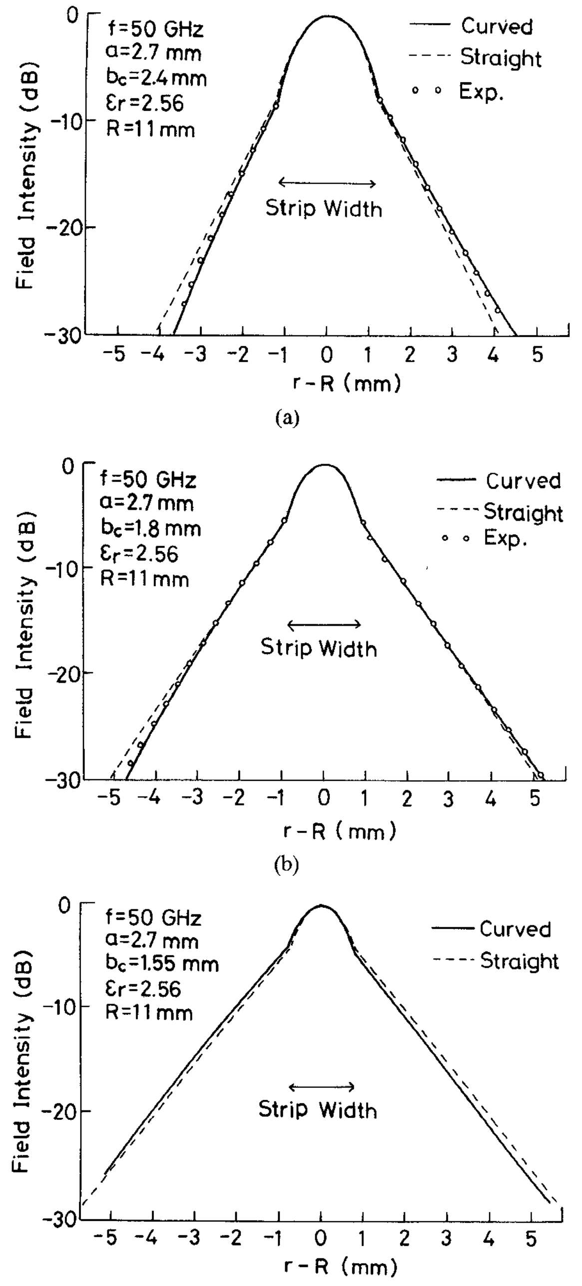

Fig. 9. Comparison of the transverse field profiles in the straight and curved NRD-guides ($R = 11$ mm). (a) $b_c = 2.4$ mm. (b) $b_c = 1.8$ mm. (c) $b_c = 1.55$ mm.

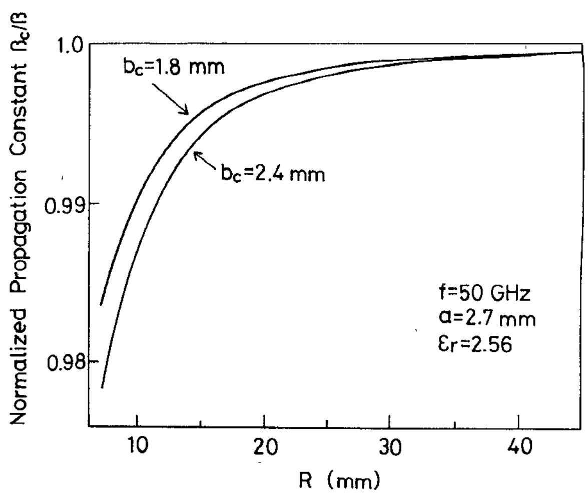

Fig. 10. Normalized propagation constant of the curved NRD-guide.

shifts. In this respect, it should be noted that the shift in the curved slab guide ($a \to \infty$ in Fig. 2) is about one order of magnitude larger than those in Fig. 8, say, $\Delta = 0.125$ mm for $R = 20$ mm and $b_c = 2.4$ mm. The advantage of the NRD-guide is obvious, since the reflection due to the field mismatch is expected to be very small. Another feature which Fig. 8 reveals is the inward shift of the field maximum for the dielectric strips which are narrower than a critical width, that is, $b_c = 2.1$ mm in the present case. The inward shift of the dominant mode field maximum is peculiar to the NRD-guide and may be attributed to the negative effective dielectric constant outside the dielectric core region, which is likely to push electromagnetic waves inwards. Collating Fig. 8 with the experimental results presented in the previous section manifests the interesting fact that the bending losses are particularly small when the width of the strip is around the critical width or slightly less than it. This seems to suggest adopting the critical width as a design criterion of the NRD-guide bend.

Further support to this remark is given in Fig. 9(a)–(c), where the theoretical field profiles of the curved guides are compared to those of the straight guides. Experimental data are also included in Fig. 9(a) and (b). The widths of the strips are $b_c = 2.4$ mm, 1.8 mm, and 1.55 mm in Fig. 9(a)–(c), respectively, while the radius of bending is $R = 11$ mm for all the cases. Among the three figures, the field deformation at the bend is least in Fig. 9(b), regardless of the fact that all have the same bending radius. Though it is too small to be recognized in the figures, the shift of the field maximum is outward in Fig. 9(a) ($\Delta = 0.0125$ mm), while it is inward, but too large in Fig. 9(c) ($\Delta = -0.0417$ mm). Only the shift in Fig. 9(b) is properly inward ($\Delta = -0.0233$ mm) and leads to a substantial reduction of the reflection at the bend as is seen in Fig. 5(a) and (b), though the width of the strip is not exactly $b_c = 1.8$ mm, but 1.9 mm there. Therefore, it is admissible to accept the critical width as a convenient design criterion of low loss, sharp NRD-guide bends. The design rule is to make the shift of the field maximum around $\Delta = 0 \sim -0.03$ mm.

At this point, a few comments are appropriate. The criterion for the bend does not necessarily hold for the straight guide. The transmission loss along the straight section is rather large for such a narrow strip due to the inherent nature of the NRD-guide. The narrow strip is effective only at the bend and it should be widened at the straight section by means of a proper taper. Furthermore, it should be noted that the strip does not have to be narrowed at the bend of a large curvature radius, say, larger than $R = 20$ mm, as shown in Fig. 3. Narrowing the strip is particularly useful for realizing a very sharp bend whose radius of bending is between one and two guide wavelengths.

Finally, the propagation constant β_c along the mean path of the bend is plotted as a function of R in Fig. 10 in the normalized form with respect to the propagation constant β of the straight guide. The dominant mode becomes a fast wave at the curved section. This is in contrast to the case of dielectric rod transmission line bends [9].

IV. Conclusions

Measurements were made of NRD-guide bends. The bending losses were found to be very small even at very sharp bends of bending radii as small as one guide wavelength. Though the transmission loss of the NRD-guide increases slightly due to the relatively small sidewall separation, the reduction in the bending loss covers this disadvantage completely. Since sharp bends are available, the NRD-guide is believed to be very useful for realizing complicated waveguide components for millimeter-wave integrated circuit applications.

The theory presented here can explain only some limited aspects of the bends in the NRD-guide, hence it has to be further improved to achieve quantitative agreements with the measurements. The mode conversion seems to be the primary candidate which has to be taken into account for a better understanding of the field behavior at the bend. Such an approach is being tried with good prospects for the completeness of this research.

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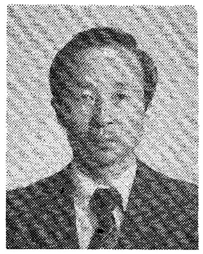

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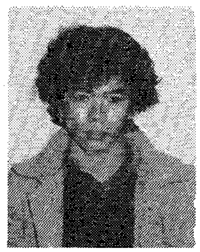

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