# Analysis and Measurements of Nonradiative Dielectric Waveguide Bends

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**Abstract**

The coupling theory is applied to analyze bending loss characteristics of the nonradiative dielectric waveguide. As an application of the theory, a low loss 180° bend with a curvature radius of 5 mm was fabricated and successfully tested at 50 GHz. The measured bending loss never exceeded 0.3 dB.

## I. Introduction

Since the advent of the NRD-guide (Nonradiative Dielectric Waveguide) in 1981[1], much effort has been devoted to the development of various circuit components, but the bends still remain to be studied further. Recent measurements have revealed that coupling between the operating and the parasitic modes at the curved section is the main origin of the bending loss. With this in mind, the two-mode coupling theory[2] is applied to analyze loss characteristics of the bends in the NRD-guide. The coupling coefficient, which plays a key role in the analysis, is rigorously calculated by taking into account the metric coefficients of the curved coordinates appropriate to the bend under consideration.

By using the design diagrams established here, a low loss 180° bend having a bending radius as small as 5 mm was fabricated and tested at 50 GHz. The measured loss was found to be less than 0.3 dB over the 2 GHz tuning range of an oscillator employed. This is surprising considering a large amount of radiation loss which is encountered in conventional image guide bends[3].

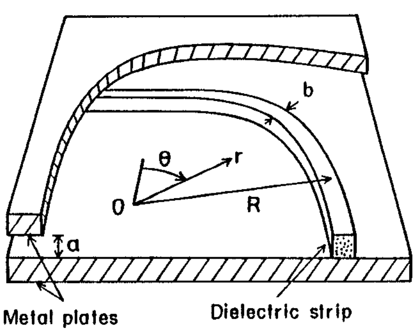


Fig.1 NRD-guide bend

## II. Calculation and Discussion

Consider a circularly curved NRD-guide bend whose height and width are a and b, respectively, and whose curvature radius is R as shown in Fig. 1. The height should be less than half a wavelength to assure the NRD-quide operation. The operating mode of the straight NRD-guide is the hybrid $LSM_{01}$ mode with no magnetic component normal to the air-dielectric interfaces[4]. Besides the $LSM_{01}$ mode, additional modes need to be considered at the bend to satisfy the more complicated boundary conditions. Among them, the $LSE_{01}$ mode is most significant since it is nonradiating in nature and, in addition, it has a phase constant closest to that of the operating mode. Therefore, only the $LSM_{01}$ and $LSE_{01}$ modes will be taken into account in the following analysis. The $LSE_{01}$ mode, in contrast to its counterpart, has no electric field component normal to the air-dielectric interfaces.

Starting with Maxwell's equations, the well known coupling equations[2] can be derived as

$$da_1/dz = -j\beta a_1 - jca_2 \quad (1a)$$

$$da_2/dz = -jca_1 - j\hat{\beta} a_2 \quad (1b)$$

where $a_1$ and $a_2$ are the complex amplitude coefficients of the forward travelling $LSM_{01}$ and $LSE_{01}$ modes, respectively, $\beta$ and $\hat{\beta}$ are the corresponding phase constants given by

$$\beta = \sqrt{[\epsilon_r k_0^2 - q^2 - (\pi/a)^2]} \quad (2a)$$

$$\hat{\beta} = \sqrt{[\epsilon_r k_0^2 - \hat{q}^2 - (\pi/a)^2]} \quad (2b)$$

and c is the coupling coefficient which is obtained here as follows:

$$c = \frac{\sqrt{[\varepsilon_r(\varepsilon_r-1)]}}{h\hat{h}ab} \frac{q\hat{q}}{(q^2-\hat{q}^2)R} \tag{2c}$$
$$\frac{2\pi p[\sqrt{(\beta/\hat{\beta})}+\sqrt{(\hat{\beta}/\beta)}]}{\sqrt{\{[(q^2+\varepsilon_r^2 p^2)+2\varepsilon_r(\varepsilon_r-1)k_0^2/pb](1+2/\hat{p}b)\}}}$$

In the above equations, $k_0$ is the free space wavenumber, $\varepsilon_r$ is the relative dielectric constant of the strip, and h and $\hat{h}$ are defined by

$$h^2 = \varepsilon_r k_0^2 - q^2 = k_0^2 + p^2 \tag{3a}$$
$$\hat{h}^2 = \varepsilon_r k_0^2 - \hat{q}^2 = k_0^2 + \hat{p}^2 \tag{3b}$$

where q, p, $\hat{q}$ and $\hat{p}$ are the first eigenvalues of the following characteristic equations, respectively:

$$q\tan(qb/2) = \varepsilon_r p, \quad q^2 + p^2 = (\varepsilon_r - 1)k_0^2 \tag{4a}$$
$$\hat{q}\tan(\hat{q}b/2) = \hat{p}, \quad \hat{q}^2 + \hat{p}^2 = (\varepsilon_r - 1)k_0^2. \tag{4b}$$

Solving (1) under the intial conditions

$$a_1(0) = 1, \quad a_2(0) = 0 \tag{5}$$

yields

$$a_1(z)=\exp(-j\beta_0 z)[\cos(\Gamma z/2)-j(\Delta\beta/\Gamma)\sin(\Gamma z/2)] \tag{6a}$$
$$a_2(z)=-j(2c/\Gamma)\exp(-j\beta_0 z)\sin(\Gamma z/2) \tag{6b}$$

where

$$\beta_0 = (\beta + \hat{\beta})/2 \tag{7a}$$
$$\Delta\beta = \beta - \hat{\beta} \tag{7b}$$
$$\Gamma = \sqrt{(\beta^2 + 4c^2)}. \tag{7c}$$

Accordingly, the bending loss can be calculated as follows:

$$L = -10\log[1 - (4c^2/\Gamma^2)\sin^2(\Gamma z/2)] \quad \text{(in dB)}. \tag{8}$$

Polystyrene($\varepsilon_r$=2.56) 2.7 mm in height but having different widths are assumed throughout the paper for carrying out numerical computation at center frequency of 50 GHz. First of all, the bending loss of the 90° bends is calculated as a function of the strip width and shown in Fig.2. The bending loss undulates at first and then increases monotonously as the strip width increases. This is also the case for the 180° bends. Figure 2 also reveals that the bending loss vanishes and is maximized at certain dielectric strip width for a given curvature radius of bend. Such relations between the curvature radius and the strip width are plotted for both the 90° and 180° bends in Fig. 3. The solid curves correspond to the lossless bend, while the dotted ones correspond to the maximum loss bend.

## III. Bending Loss Measurements

The diagrams in Fig. 3 are especially useful for designing bends of minimum loss. A 180° bend, for instance, is lossless if a strip width of 2.5 mm is chosen for a curvature radius of 5 mm. A 90° bend with a strip width of 2.5 mm and a curvature radius of 10 mm is also lossless. Loss measurements of these two bends connected in tandem were made. The 90° bend was incorporated to avoid mechanical as well as electrical interference between the transmitting and receiving horns which would occur with the 180° bend alone. The fabricated bend is shown in Fig. 4.

Bending losses were measured by comparing transmissions of the compound bend and a straight strip equal in length. The obtained results are shown in Fig. 5 over a frequency range from 49 to 51 GHz of the manual tuning klystron oscillator. The overall bending loss was found to be less than 0.3 dB. This residual loss may be in part due to the avoidable measurement error and in part due to the nontrivial reflection at such sharp bends.

## IV. Conclusions

The NRD-guide bend is analyzed by means of the coupling theory. It is found that the bending loss can be minimized if the strip width is optimized for a given curvature radius of bend at a specified frequency. A very sharp 180° bend with a curvature radius of 5 mm was fabricated at 50 GHz and its bending loss was found to be less than 0.3 dB.

This clearly shows the advantage of the NRD-guide over other dielectric waveguides which suffer from a large amount of radiation at bend.

## References


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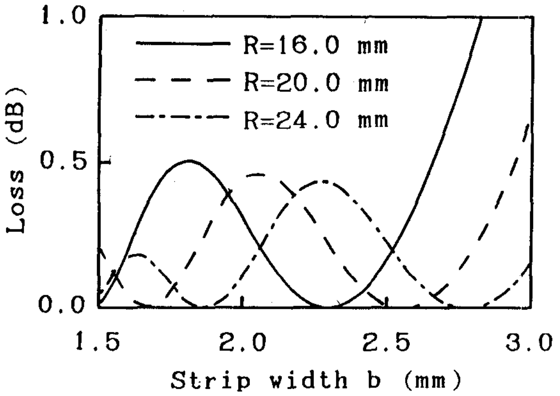


Fig.2 Bending loss of the polystyrene 90° NRD-guide bend at 50 GHz as a function of the strip width for various radii of curvature

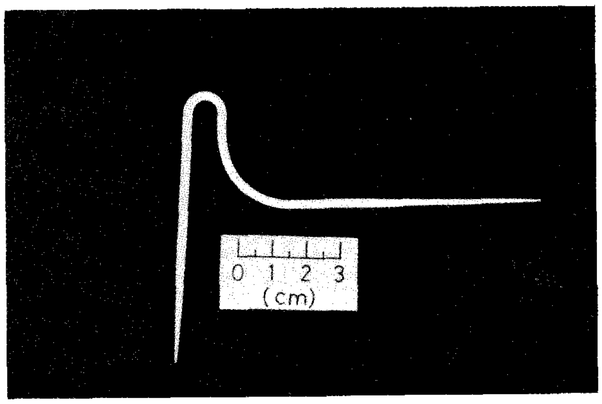


Fig.4 Photograph of fabricated NRD-guide compound bend

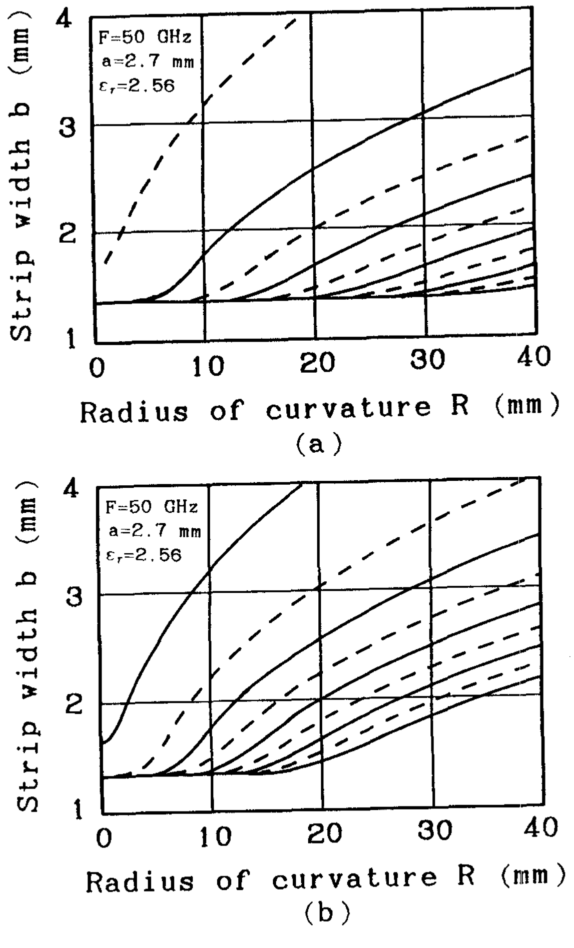


Fig.3 Design diagrams for (a) 90° and (b) 180° polystyrene NRD-guide bends 2.7 mm in height at 50 GHz. Solid and dotted curves correspond to the lossless and maximum loss bends, respectively

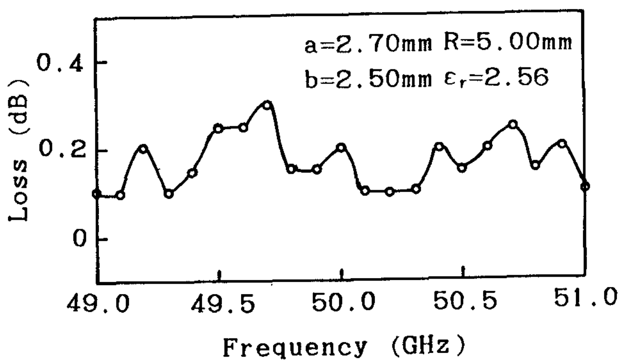


Fig.5 Measured bending loss of the compound bending structure consisting of 180° and 90° bends connected in series