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The Effects of Bends in Waveguides for Aviation and Non-Aviation Applications

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Abstract

Waveguides, one of the most effective ways to carry electromagnetic energy, have application areas such as microwave communication systems, internet networks, radars, space exploration, optics and aviation. Sudden changes in the size or shape of the waveguides, such as bends and twists, can cause reflections and overall loss of efficiency. When such a change is required, the bends and twists of the waveguides must provide certain conditions to prevent reflections. This paper describes a new method to evaluate the attenuation constant for a circular dielectric or metallic waveguide having uniform curvature. When the radius of curvature "R_o" is large compared to the radius "a" of the waveguide (i.e. $R_o >> a$), field components can be obtained directly using toroidal coordinate system for the curved section of the waveguide instead of obtaining from those obtained for straight waveguide using perturbation techniques. Results obtained show excellent agreement with those given in the literature.

Keywords: Waveguides, Bends, Microwave

Dalga Kılavuzlarındaki Bükülmelerin Havacılık ve Havacılık Dışı Uygulamalara Etkileri

Öz

Elektromanyetik enerji taşımanın en etkili yollarından biri olan dalga kılavuzları, mikrodalga iletişim sistemleri, internet ağları, radarlar, uzay araştırmaları, optik ve havacılık gibi uygulama alanlarına sahiptir. Kıvrım ve bükülmeler gibi dalga kılavuzlarının boyutunda veya şeklindeki ani değişiklikler yansımalara ve genel verimlilik kaybına neden olabilir. Böyle bir değişiklik gerektiğinde, dalga kılavuzlarının kıvrımları ve bükülmeleri yansımaları önlemek için belirli koşullar sağlamalıdır. Bu makalede, düzgün bir eğriliğe sahip dairesel dielektrik veya metalik dalga kılavuzu için zayıflama sabitini değerlendirmek için yeni bir yöntem

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açıklanmaktadır. "R_0" eğrilik yarıçapı, dalga kılavuzunun (R_0 >> a) yarıçapı "a" ile karşılaştırıldığında büyük olduğunda, alan bileşenleri dalga kılavuzunun kavisli kısmı için doğrudan toroidal koordinat sistemi kullanılarak elde edilebilir. Düz dalga kılavuzu için pertürbasyon teknikleri kullanılarak elde edilir. Elde edilen sonuçlar literatürde verilenlerle mükemmel bir uyum göstermektedir.

Anahtar kelimeler: Dalga kılavuzu, Bükülmeler, Mikrodalga

INTRODUCTION

Waveguides are special dielectric or metallic structures through which the electromagnetic waves are transmitted. Thanks to their low-loss transmission and geometries, they provide the ability to combine, filter, mix, phase shift and otherwise manipulate electromagnetic waves. Waveguides, one of the most effective ways to carry electromagnetic energy, have many advantages over two-wire transmission lines and coaxial cables. The two-wire transmission line used in conventional circuit designs cannot be used in high frequency electromagnetic energy transfer due to the skin effect. Therefore, waveguides are used instead of two-wire transmission lines at high frequencies such as microwave, infrared and optical frequencies.

The waveguides are normally rigid, and therefore, when it is necessary to direct the waveguide in a certain direction, the waveguide can be bent in the desired direction. However, any abrupt changes in the shape of the waveguide, such as bends or twists, can cause reflections and overall loss of efficiency. When such a change is required, the bends and twists of the waveguides must provide certain conditions to prevent reflections and reduce the attenuation constant (Sun, Yu, Chen and Zhang, 2017).

Waveguides have application areas such as microwave communication systems, internet networks, radars, space exploration, optics and aviation. One of the aviation applications of waveguides is the application of optical waveguide technology to head mounted display solutions. Today, holographic optical waveguide technology has many aviation and non-aviation applications for helmet-mounted displays (Cameron, 2012). Waveguides can also be used in many fiber-optic applications, such as optical sensors, fiber-optic gyroscopes, variable delay lines, optical buffers for packet switching, opto-electronic oscillators, and narrow-band filters (Heck, Bauters, Davenport, Spencer and Bowers, 2014)

Increase in the attenuation constant due to curvature is a series problem in dielectric or metallic waveguides. As the radius of curvature decreases the attenuation constant and thus the power losses increase. Therefore, it is important to determine the change in the attenuation constant due to the chance in the radius of curvature (Unal, 1994).

Most of the methods described in the literature make use of perturbation techniques in order to express the fields in a curved waveguide in terms of the modes in a straight waveguide thereby requiring long and cumbersome calculations. In some studies, the terms of the order $(1/R_o)^2$ has been neglected, so its results are not compatible with other studies (Miyagi, Harada and Kawakami, 1984). On the other hand, methods based on mode coupling are not always applicable to infrared metallic waveguides (Miyagi, Harada and Kawakami, 1984). Other analysis for evaluating attenuation constant of curved waveguides having arbitrary cross-sectional areas is based on surface impedance and admittance concepts (Marhic, 1981).

In this paper, however, a simpler method is presented to investigate the effect of curvature on the attenuation constant in a circular dielectric or metallic waveguide.

1. FORMULATION

The geometry for a circular waveguide is shown in Fig.1. To simplify mathematics, analysis is restricted to the modes with $\beta = k_o$, where β is the propagation constant and $k_o = 2\pi/\lambda$. The radius "a" is assumed to be much larger than free space wavelength λ.order to express the field components in terms of a scalar function, the following conditions has to be satisfied (Bohn, 1968).

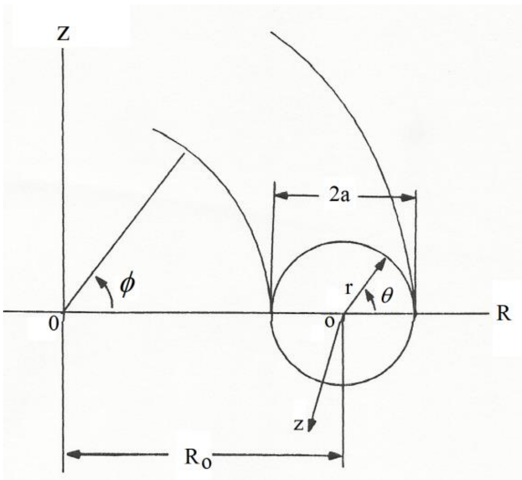

Figure 1. Geometry of the Curved Circular Waveguide

$$\frac{\partial}{\partial z}\left(\frac{h_r}{h_\theta}\right) = 0, \quad h = 0 \tag{1}$$

where, h_r, h_θ and $h(= h_z)$ are metric coefficients in the toroidal coordinate system and are given as

$$h_r = 1,\ h_\theta = r,\ h = 1 + \frac{r}{R_o} cos\theta \tag{2}$$

It is clear that, if $R_o \gg a$, the conditions given in (1) are satisfied.

Scalar functions inside the curved waveguide (i.e. $r < a$) can be written in the following form when $e^{j(\omega t - \beta z)}$ terms are omitted;

$$\psi^i = \begin{cases} A_n J_n(k_h r)\cos(n\theta + \theta_o) & \text{for TM waves} \\ B_n J_n(k_h r)\sin(n\theta + \theta_o) & \text{for TE waves} \end{cases} \tag{3}$$

where k_h is

$$k_h = \left(k_o^2 \eta_o^2 - \frac{\beta^2}{h^2} \right)^{1/2} \tag{4}$$

Using (2) in (4) and then expanding the right hand side into a Binomial series in terms of $(1/R_o)$ yield for k_h;

$$k_h = k_i + k_i \left(\frac{k_o^2}{k_i^2} \right) \frac{r}{R_o} \cos\theta - k_i \left(3\frac{k_o^2}{k_i^2} + \frac{k_o^4}{k_i^4} \right) \frac{r^2}{2R_o^2} \cos^2\theta + \dots \tag{5}$$

On the other hand, for the external region, $r > a$, the solution takes the form

$$\psi^e = \begin{cases} C_n H_n^{(2)}(k_{he} r)\cos(n\theta + \theta_o) & \text{for TM waves} \\ D_n H_n^{(2)}(k_{he} r)\sin(n\theta + \theta_o) & \text{for TE waves} \end{cases} \tag{6}$$

And similarly, k_{he} can be expressed as

$$k_{he} = k_e + k_e \left(\frac{k_o^2}{k_e^2} \right) \frac{r}{R_o} \cos\theta - k_e \left(3\frac{k_o^2}{k_e^2} + \frac{k_o^4}{ke_i^4} \right) \frac{r^2}{2R_o^2} \cos^2\theta + \dots \tag{7}$$

Here, J_n and $H_n^{(2)}$ are the first kind Bessel and second kind Hankel functions of order n respectively, A_n, B_n, C_n, and D_n are constant coefficients.

The total field in each region is then expressed as the sum of TE and Tm fields which can be obtained in terms of ψ^i and ψ^e (Bohn,1968). Only the modes with $n = 0$ are pure TE or TM and the remaining modes are hybrid in form, possessing angular θ variation.

Finally, complete field expression in terms of powers of $(1/R_o)$ in curved waveguide are obtained for both $r < a$ and $r > a$ by substituting (5) and (7) into the expressions for the total fields and using the Bessel function expansion given in (Unger, 1957).

The relationship between the mode coefficients A, B, C and D is determined by enforcing the boundary conditions across the curved boundary.

The attenuation constant α is derived by means of a perturbation method is widely used in the evaluation of attenuation for low loss systems (Marcatili and Schmeltzer, 1964), namely,

$$\alpha = \frac{1}{2} \frac{P_r}{P_z} \tag{8}$$

Here, P_r is the average power radiated from waveguide per unit length and P_z is the power in z direction within the internal region. Using the external fields at $r = a$, P_r can be determined by using the following equation (Marcatili and Schmeltzer, 1964).

$$P_r = \frac{1}{2} R_e \int_0^{2\pi} \left[E_\theta H_z^* - E_z H_\theta^* \right] \left(1 + \frac{a}{R_o} \cos\theta \right) a d\theta, \tag{9}$$

And employing the fields in $r < a$, P_z can be calculated from;

$$P_z = \frac{1}{2} R_e \int_o^a \int_0^{2\pi} \left[E_r H_\theta^* - E_\theta H_r^* \right] \left(1 + \frac{a}{R_o} \cos\theta \right) r dr d\theta, \tag{10}$$

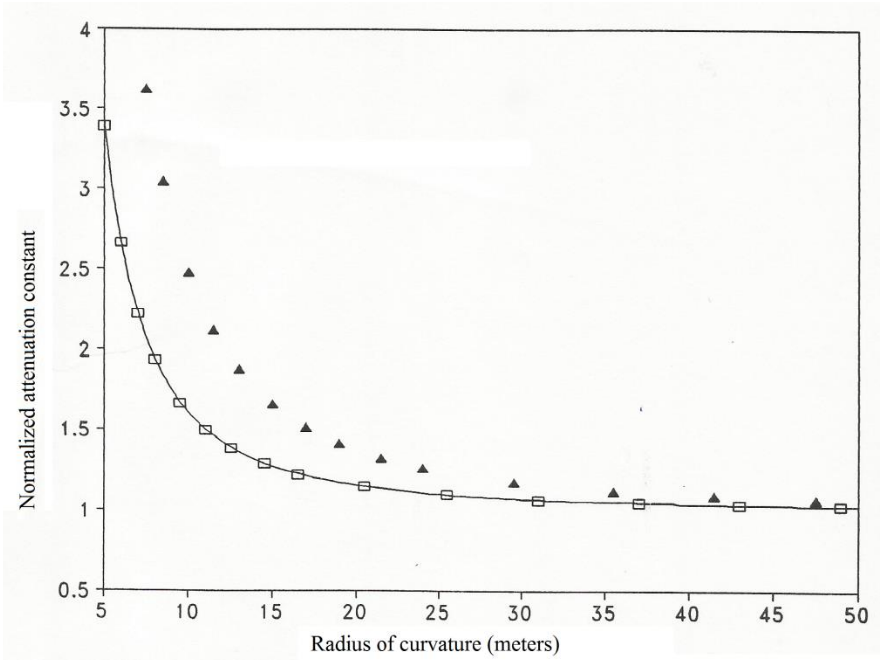

Figure 2. The Normalized Attenuation Constant of HE_{11} Mode for a Bent Aluminium Waveguide.

2. RESULTS

Numerical Results of the attenuation constants are obtained using (8) and normalized by that for a straight waveguide. Variation of the normalized attenuation constants of HE_{11} mode as a function of the radius of the curvature Ro is shown in Fig.2 for a bent aluminium waveguide with a refractive index $\eta = 20{,}5 - j58{,}6$, $a = 500\mu m$, and $\lambda = 10{,}6\mu m$. The results obtained in this study are compared with the results given in the literature and it is seen that the results are in good agreement especially as the bending radius increases (Marcatili and Schmeltzer, 1964).

The orientation of the fields with respect to the plane of the curvature influences only the HE_{1n}, and EH_{1n} modes. The remaining modes are independent of the orientation θ_o. In Fig.2, the value of θ_o is taken to be zero.

3. CONCLUSION

The proposed method can be applied to any curved circular waveguide an long as $R_o \gg a$. However, it is important to realize that even though the expressions obtained for ψ do not satisfy the actual boundary conditions exactly, the error will be small, and is in the order of $(1/R_o)^3$. Since the effect of the external region is not represented by equivalent surface impedances and admittances, proposed method can be used to solve a larger class of curved waveguide problems than considered in the literature. Also the simplicity of the field equations is an advantage in writing the computer codes. As a result, the proposed method can be applied to any curved circular waveguide provided that as $R_o \gg a$ and can be used in microwave communication systems, internet networks, radars, space exploration, optics and aviation applications.

REFERENCES

Bohn, E.V. (1968). *Introduction to electromagnetic fields and waves,* Addison-Wesley Pun.

Cameron, A.A. (2012). Optical waveguide technology and its application in head- mounted displays. *Head and Helmet-Mounted Displays XVII; and Display Technologies and Applications for Defense, Security, and Avionics VI. 83830E* (pp 1-11), https://doi.org/10.1117/12.923660.

Gabrielli, L. H., Liu, D., Johnson, S. G., & Lipson, M. (2012). On-chip transformation optics for multimode waveguide bends. *Nat. Commun. 3*(1), 12-17.

Heck, M., Bauters, J., Davenport, M., Spencer, D., & Bowers, J. (2014). Ultra-low loss waveguide platform and its integration with silicon photonics. *Laser Photonics Rev. 8* (5), 667-686.

Jiang, X., Wu, H., & Dai, D. (2018). Low-loss and low-crosstalk multimode waveguide bend on silicon. *Optics Express, 26*(13), 17680-17689.

Marcatili, E.A.J., & Schmeltzer, R.A. (1964). Hollow metallic and dielectric waveguides for long distance optical transmission and lasers. *Bell Syst. Tech.J., 43*,1783-1809.

Marhic, M.E. (1981). Mode-coupling analysis of bending losses in IR metallic waveguides. *Appl. Opt. 20*, 3436-3441.

Miyagi, M. (1985). Complex propagation constant of bent hollow waveguise with arbitrary cross section. *IEEE Trans. Microwave Theory Tech, 33*, 15-19.

Miyagi, M., Harada, K., & Kawakami, S. (1984). Wave propagation and attenuation in the general class of circular hollow waveguides with uniform curvature. *IEEE Trans. Microwave Theory Tech, 32*, 513-521.

Unger, H.G. (1957). Circular electric wave transmission in dielectric coated waveguide. *Bell Syst.Tech.J., 36*, 1253-1278.

Ünal, E. (1994). *Evaluation of the attenuation constant for curved cylindrical hollow dielectric or metallic waveguide*, A Ph. D. Thesis. Electrical and Electronics Engineering, University of Gaziantep.

Sheehan, R.N., Horne, S., & Peters F.H. (2008). The design of low-loss curved waveguides. *Optical and Quantum Electronics, 40*(14), 1211-1218.

Sun, C., Yu, Y., Chen, G., & Zhang, X. (2017). Ultra-compact bent multimode silicon waveguide with ultralow inter-mode crosstalk. *Opt. Lett. 42*(15), 3004-3007.

Tu, X., Li, M., Jiang, J., Goodwill, D., Dumais, P., Bernier, E., Fu, H., & Geng, D. (2016). Compact low-loss adiabatic bends in silicon shallow etched waveguides. *in Proceedings of IEEE International Conference on Group IV Photonics*, pp. 48-49.

Wu, X., Zhou,W., Huang, D., Zhang, Z., Wang, Y., Bowers, J., & Tsang, H. K. (2018). *Low Crosstalk Bent Multimode Waveguide for On-chip Mode-Division Multiplexing Interconnect,* in Conference on Lasers and Electro-Optics, OSA Terchnical Digest (online), paper JW2A.66.

Xu, H., & Shi,Y. (2018). Ultra sharp multimode waveguide bending assisted with metamaterial based mode converters. *Laser Photonics Rev. 12*(3), 1-6.