The N-Guide: A Novel Miniaturized Hard Quasi-TEM Waveguide

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1. Introduction

Conventional metal waveguides need to have a width or diameter larger than typically 0.5λ in order to support waves. In several applications, such as e.g. multi-band arrays of slotted or open-ended waveguides, it is desirable with thinner miniaturized waveguides (one for each frequency band) that can be located side by side without introducing grating lobes in any band. Classical waveguides can be reduced in size by filling them with dielectric material, but this is not a good solution due to the losses in the dielectric, the increased weight, and because there is no air region inside where active components or tuning devices can be located. The purpose of the present paper is to introduce a new miniaturized quasi-TEM N-guide that is mainly air-filled. It is a folded version of the hard dielectric-loaded rectangular waveguide studied in [1].

Previously, waveguides of compact cross-sections have been realized via deformation of the cross-sections (such as bending and folding). Examples are the ridge (or π) and the H-waveguides. Extensive study on the ridge waveguide has already been performed, with an early paper in [2] while more recent ones are found in e.g. [3][4] investigating slotted ridge waveguides. Waveguides of other complex cross-sections have been discussed in [5]. In view of this, the new N-guide exhibits a complex cross-section, as described in [5], though it has a cross-sectional shape different from any of those considered there. It is also a hard waveguide [6] capable of propagating a quasi-TEM wave when operated at some particular TEM frequency as it is based on the concept of the conventional dielectric-loaded hard-walled rectangular waveguide [1][7][8]. Another related form of such a structure is the TEM waveguide involving a so-called electromagnetic bandgap lattice etched on a conductor-backed dielectric slab [9]. Consequently, when such structures are used, free-space quasi-plane wave characteristics may be demonstrated within a certain frequency band. As in all hard waveguides, the air-filled region of the N-guide can be adjusted in cross-sectional size to fit into a desired space without affecting much the propagation constant at the TEM frequency. We refer to this property as an accordion characteristic.

Apart from presenting the transverse field distributions over the cross-section of the new hard waveguide, the dispersion characteristics of the propagation and effects of variations in physical dimension on the phase constant are also investigated.

2. Miniaturization of Hard TEM Waveguide: The N-Guide

Consider the dielectric-loaded hard-walled rectangular waveguide shown in the extreme left of Fig. 1, which undergoes various stages of folding to become a compact guide. This follows from previous practice of cross-sectional deformation. Since its shape resembles the letter N, it is referred to as the N-guide.

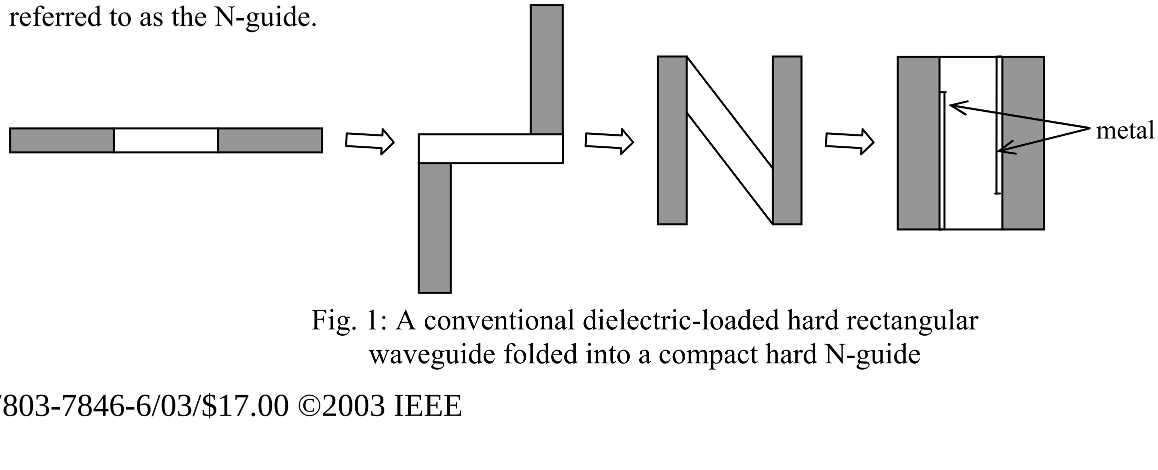

Fig. 1: A conventional dielectric-loaded hard rectangular waveguide folded into a compact hard N-guide

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The dimensions of this compact N-guide are defined in Fig. 2. In view of the folding, the dielectric thickness d in the conventionally straight unfolded hard-walled rectangular waveguide is no longer so well-defined in the N-guide. Hence, it is convenient to introduce an effective dielectric depth $d_{eff} = d - 0.5w_{interface}$, from which the associated TEM frequency can be predicted quite accurately from $f_{TEM} = \left[4d_{eff}\sqrt{\mu_0\varepsilon_0\left(\mu_r\varepsilon_r - 1\right)}\right]^{-1}$, where μ_r and ε_r are the constitutive parameters of the dielectric.

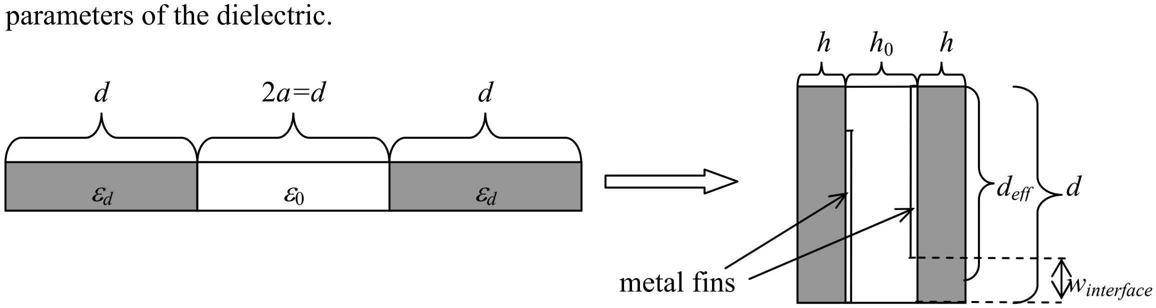

Fig. 2: Dimensions of a conventional unfolded dielectric-loaded hard rectangular waveguide and its compact N-guide counterpart

A typical N-guide having the following properties was studied. The dielectric used has complex relative permittivity of $12(1 - j1.5\times10^{-4})$ and the designed TEM frequency is 2.3 GHz with an associated dielectric depth $d = 11.3$ mm and dielectric-freespace interface width $w_{interface} =$ 3mm. The height of the top and bottom dielectric (h) is 3mm while that of the central freespace region (h_0) is 7 mm (see Fig. 1). The thickness of the metal fins inside the waveguide is 0.5mm.

3. Transverse Field over Guide Cross-Section and Dispersion Characteristics

The FEM-based simulation software HFSS was used to generate the transverse electric field distribution over the cross-section of the N-guide at the designed TEM frequency of 2.3 GHz. This is illustrated in Fig. 3a, with its dispersion graph shown alongside in Fig. 3b, which was obtained by repeating HFSS simulations at different frequencies.

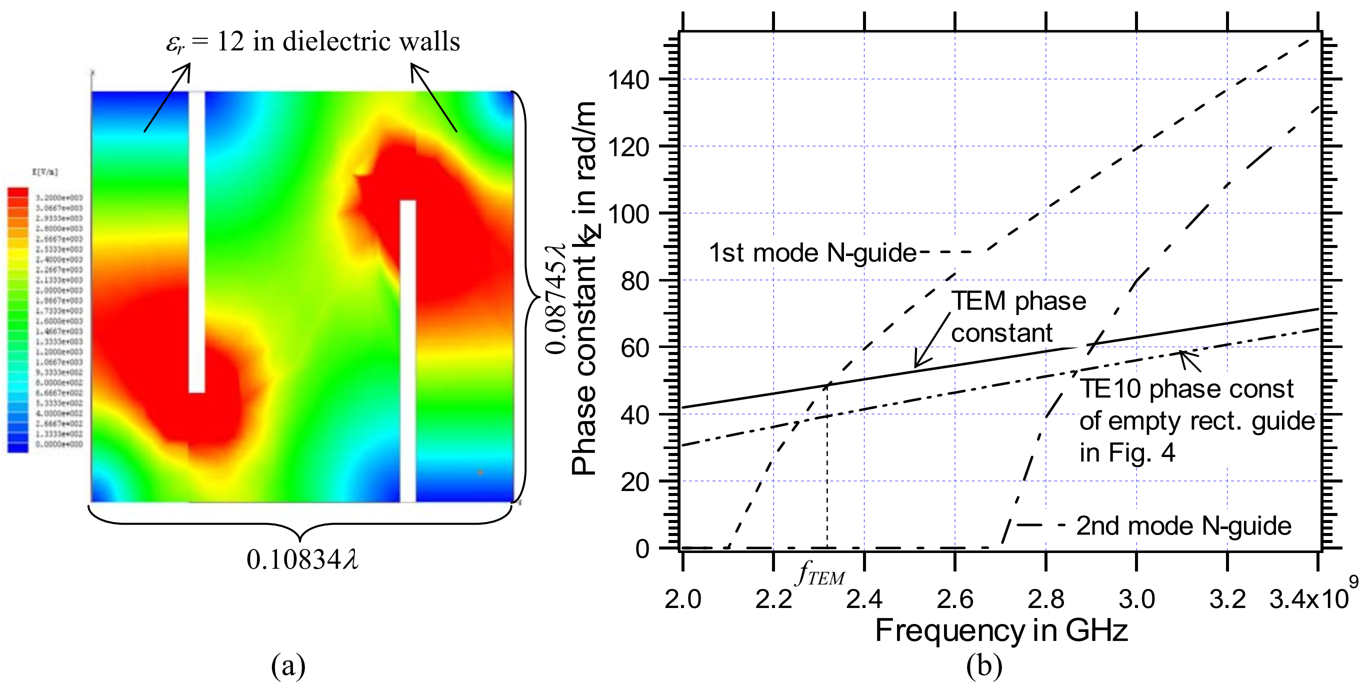

Fig. 3(a): HFSS-simulated transverse electric field distribution over N-guide cross-section (b) Dispersion graph

To obtain a better dynamic range in the plot, we have removed the peaked field values in a few cells around the sharp corners of the two inner metal walls. As observed, the transverse electric field distribution across the N-guide cross-section is similar to that in the straight unfolded conventional dielectric-loaded hard rectangular waveguide [1], in the sense that the electric field vector follows the orientation of the folding from the straight to the N-guide. The electric field vector vanishes in the bottom of the two dielectric-filled grooves. There is some field variation inside the air-filled part of the waveguide, mainly near the corners of the geometry.

The dispersion graph shows that the cutoff frequency of the most dominant mode is around 2.1 GHz while that of the next one is around 2.7 GHz. It is also seen that the TEM frequency at which the most dominant mode portrays TEM behavior (having the same phase constant as that of free space TEM plane wave) is approximately 2.32 GHz, being very close to the designed TEM frequency based on the formula in Section 2. Thus, this formula for the TEM frequency involving the effective dielectric depth is validated. Operating at this 2.32GHz TEM frequency, the dominant quasi-TEM mode is about 0.2GHz above cutoff and 0.4GHz below the cutoff of the next higher-order mode.

4. Comparison with Conventional Empty Rectangular Waveguide Operating within Same Frequency Band

To dramatize the size difference between a conventional empty rectangular waveguide operating at about the same frequency as the N-guide, the authors take pleasure in illustrating a photograph showing them placed side-by-side with each other in Fig. 4. The dimension of the N-guide is that described earlier.

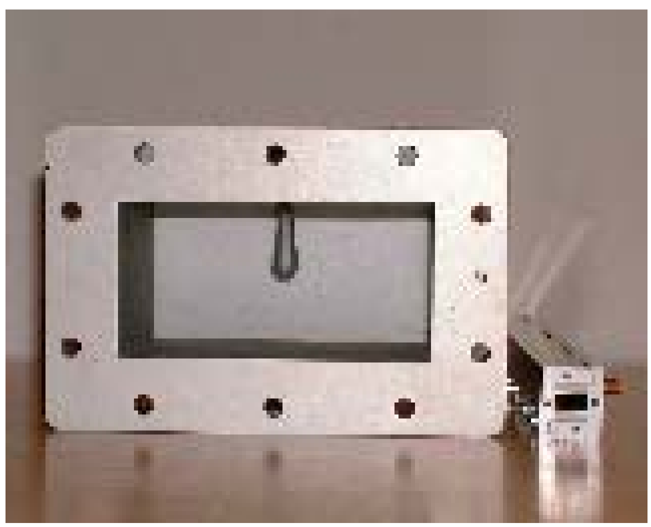

Fig. 4: Photograph comparing the cross-sectional size between a conventional empty rectangular waveguide and the N-guide, both operating at 2.3GHz. The N-guide is much more narrowband though

However, as seen from the dispersion characteristics in Fig. 3b, the N-guide does not demonstrate very broadband performance, as seen from the rather substantial deviation of the phase constant (along the propagation direction) from the freespace one for frequencies divergent from the TEM frequency. Thus, the quasi-TEM nature degrades fairly quickly as the frequency strays from the TEM frequency. On the other hand, the conventional empty waveguide is less dispersive and hence much more broadband than the N-guide, evidential from a gentler dispersion slope. However, gaining advantage in one performance, being the size, inevitably requires us to compromise in another, being the bandwidth.

Conclusion

A novel hard quasi-TEM waveguide referred to as the N-guide has been introduced. It is spawned from the concept of cross-sectional deformation (folding in this case) of the conventional dielectric-loaded hard-walled rectangular waveguide, whose dominant quasi-TEM mode exhibits uniform cross-sectional field distribution over the empty part due to the hard condition at the dielectric-freespace interface where the electric field component parallel to this interface is maximum. This behavior is redisplayed in the N-guide, in the sense that the field vectors follow the fold-orientation and demonstrate a maximum at the dielectric-freespace interface. The dispersion graph of this structure was generated, shedding light on the bandwidth of the N-guide, which is observed to be narrow. Finally, the N-guide was shown to be much smaller than a conventional empty rectangular waveguide operating at the same frequency. This demonstrates the potential of using the N-guide in multi-band superposed arrays with widely separated frequency bands. The bandwidth as well as the effect of losses, and the fields close to the ends of the inner metal walls need further investigation. The manufactured N-guide has not yet been measured, but we hope to present measurements at the conference.

Acknowledgements

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