Low Loss Integrated Waveguide Feed Network for Planar Antenna Arrays

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Abstract

A low-loss antenna feed structure, based on Substrate Integrated Waveguide (SIW) with PBG walls is proposed. The proposed structure is simulated and results are presented. A number of different waveguides are manufactured and their measurement results are given.

I. INTRODUCTION

Microstrip antenna arrays are exploited in a variety of engineering applications due to their ease of manufacturing, low-cost, low profile and lightweight. In many practical designs, a coplanar corporate feed network feeds the elements of such array in order to maintain a minimum constructional complexity and a compact size. At higher microwave and millimeter-wave frequencies, this approach suffers from ohmic and dielectric losses of the connecting microstrip lines and undesired radiation of the feed network. Therefore, the realization of high-efficiency microstrip antenna arrays with a large number of elements can be a challenging problem, unless a low-loss, low-radiation feed replaces the coplanar one.

Among all microwave transmission lines, hollow metallic waveguides feature extremely low losses up to very high frequencies and have been intensively utilized in the feed system of planar slot arrays and in the beam forming networks of satellite antennas. The authors have also proposed an ultra-low-loss waveguide feed network combined with a high gain microstrip antenna in order to enhance the overall radiation efficiency of the resulting hybrid array [1].

There are a number of drawbacks to a hybrid antenna system. First of all, the waveguide-fed antenna is bulkier due to the metallic feed network that dictates the overall size of the structure. Additionally, due to the fact that the technology is comprised of two parts – the front end aperture which is microstrip and therefore can be readily manufactured in a printed circuit board (PCB) company, and the back-end waveguide feed, which is metallic and therefore must be manufactured in a mechanical shop – creates the problems of higher assembly cost and complexity.

Hence, the ideal structure should combine the ease of manufacturing and low-cost of microstrip elements with the performance of waveguides in one substrate. Here, the authors present a novel method for an antenna feed at Ku-band, which meets both goals of very low size, and very low loss such that it can be used successfully as a corporate feed network for antenna array systems.

II. BACKGROUND

The proposed feed structure consists of a very thin waveguide integrated in a multi-layer substrate that is readily available as part of PCB manufactured circuitry. Two successive ground layers in the multilayer structure create the top and bottom walls, and the side-walls are created by a number of periodically-spaced via holes which are grounded at the top and bottom walls. The arrangement and structure of via holes creates a PBG effect and no energy is leaked through the sidewalls; that greatly eliminates loss in the feed. Similar work has been proposed in [2] for higher frequencies and for circuits where the size of the structure is less than or comparable to the wavelength, λ. In this work the distinguishing and key feature of the structure manifests itself in the form of a machined cut-out of the dielectric between the via walls such that wave propagation is taking place in air rather than in the lossy dielectric proposed in [2]. Although it can be argued that a dielectric cutout in the thin waveguide can be complex and difficult to manufacture, and therefore lead to a costly structure, recent improvements in PCB manufacturing practices greatly eliminate this concern. The presented manufactured structures confirm this as will be seen later in this paper.

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In Fig. 1 two low-loss waveguide structures are presented. Fig. 1(a) illustrates the typical metallic waveguide such as the one investigated in [1] for Ku-band, which consists of all-solid conducting walls and can be manufactured from two pieces of extruded/milled metal, depending on the overall feed configuration [3]. Fig. 1(b) presents the proposed waveguide with PBG walls, where the center of the waveguide is hollow and, hence supports low-loss propagation of energy. The sidewalls are formed by via arrangements in PBG patterns, although for simplicity we show only one row of closely spaced vias in Fig. 1(b). As previously mentioned, the top and bottom walls are the ground metallic layers of successive multilayer dielectric.

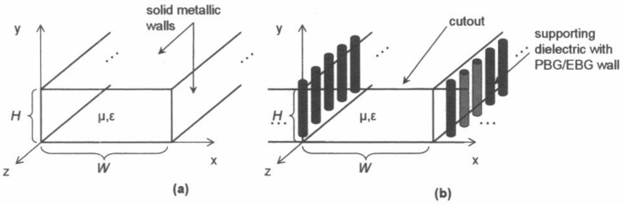


Fig. 1. Waveguide structure for low-cost antenna feed.
a. Metallic waveguide. b. Substrate integrated waveguide.

In traditional metallic waveguide structures, the width W of the waveguide is chosen for propagation of the dominant TE_{10} mode with all other modes being in cutoff. The height H is chosen conveniently to be a ratio of the width and to minimize the overall loss. For example, at Ku-band satellite frequencies (12.20 – 12.70 GHz), the *WR75* standard provides $W = 19.05$ *mm* (0.75 *in*) and $H = 9.525$ *mm* (0.375 *in* = $0.5W$) with frequency mode of operation of 10.00 – 15.00 *GHz*. In the case of PBG/EBG-wall waveguide, W can be chosen arbitrarily as long as the cutoff frequency condition is maintained for the waveguide using the formulation: $f_{c10} = 1/(2W\sqrt{\mu\varepsilon})$, where f_{c10} is the waveguide cutoff frequency for the TE_{10} mode, and μ, ε are the permeability and permittivity of the material in the waveguide respectively (air in this case). H, however, is dictated by the thickness of the substrate chosen for the waveguide implementation.

III. DESIGN

In Fig. 2 a cross-section of an overall antenna structure is illustrated. This section is composed of a 4-layer combined antenna and feed section that can be used as part of a larger antenna structure. The supporting substrate can be low-cost FR4 provided that dielectric cutouts are used in the waveguide feed as previously mentioned.

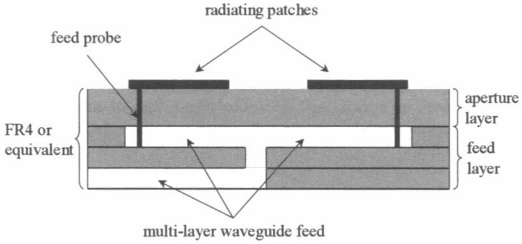


Fig. 2. Cross section of multi-layer PBG/EBG-waveguide feed structure

We choose the cutoff frequency of the TE_{10} mode to be 10 *GHz* which results in $W = 15$ *mm* for the waveguide. Additionally, since we are proposing the waveguide to be used in a multi-layer environment, such as the one shown in Fig. 2, the height H should ideally be as small as possible. We choose a standard FR4-dielectric implementation and $H = 0.508$ *mm* (20 *mil* dielectric thickness).

In the first step, in order to validate the low-loss waveguide structure, two waveguides of lengths L_1 and L_2 were manufactured in order to estimate the loss of the final structure. Due to non-standard waveguide sizes, careful consideration must be given to measurement of the final manufactured device, which in turn must be used in the simulation in order to allow for a good comparison between simulation and measurement data. Therefore, standard SMA-type connectors were used for the 2-port waveguide structure and their effects were de-embedded from the two measurements in order to obtain the characteristics of the waveguide alone.

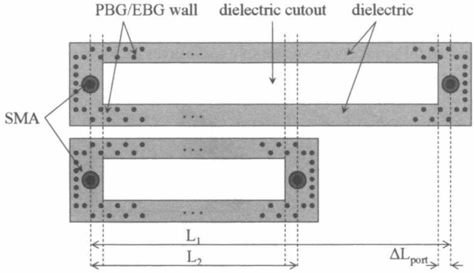
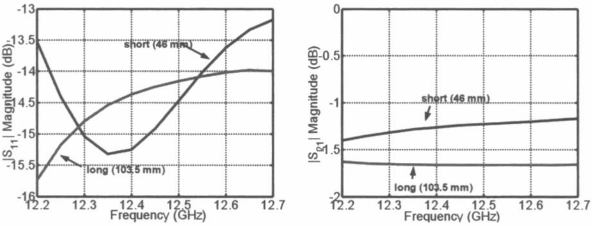


Fig. 3. Top view of two different-length multi-layer PBG/EBG-waveguide feed structures.

The two waveguides proposed are shown in Fig. 3. Each is a 2-port structure having SMA-input and output connectors for measurement. The center pin of each SMA connector is supported in a thin dielectric substrate that has little impact on the matching of the transition. In Fig. 3, ΔL_{port} is the physical distance between the SMA center conductor and the dielectric cutout portion of the waveguides, and is later de-embedded from measurements.



(a) (b)

Fig. 4. Simulation results. (a) $|S_{11}|$ Magnitude. (b) $|S_{21}|$ Magnitude.

A. Simulation Results

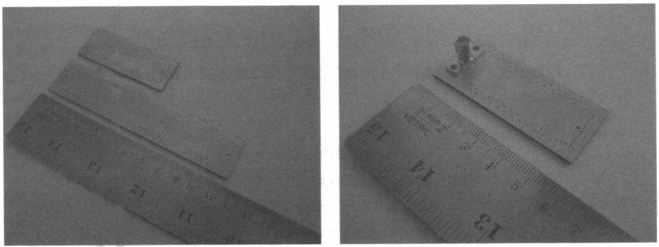
The structures presented in Fig. 3 are simulated for $L_1 = 46\ mm$ and $L_2 = 103.5\ mm$, having $\Delta L = L2 - L1 \sim 2\lambda_g$. A low-loss SMA-waveguide transition (not discussed here) for each input/output is designed with a return loss of at least -20 *dB*. The return loss of manufactured waveguides is shown in Fig. 4 (a). The insertion loss is presented in Fig. 4 (b). As illustrated, $|S_{21\text{-}short}| = -1.25$ *dB* at f = *12.45* GHz, while the $|S_{21\text{-}long}| = -1.6$ *dB* at f = 12.45 *GHz*.

B. Prototype Fabrication

The waveguides are manufactured using standard PCB techniques, with the distinction of the cutout section that is obtained in the PCB process using an extra stamping step, before bonding the layered structure together. The resulting structures are illustrated in Fig. 5, showing the two different lengths (a) as well as the SMA-connector on one end of the waveguide (b).

C. Measurement Results

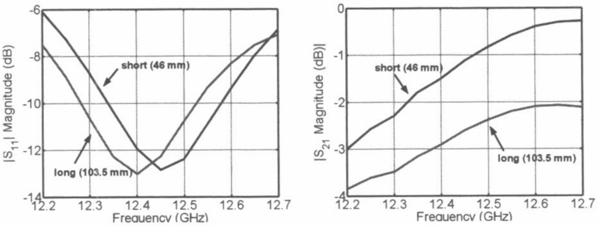
The manufactured waveguides are measured using an Agilent 8722 VNA and the results are illustrated in Fig. 6. For the Ku-band frequency of interest (12.20 – 12.70 *GHz*), the $|S_{11}|$ shown in Fig. 6 (a) is acceptable in the mid-band but is relatively low at the lower and upper frequency edges. The $|S_{21}|$ in the same frequency band is acceptable at higher frequencies (>12.45 *GHz*), but



(a) (b)

Fig. 5. Fabricated waveguides. (a) L_1 and L_2 –length waveguides.
(b) SMA connector to waveguide for measurement and characterization.

increases for lower frequency values. The main reason for differences between simulated and measured behavior is the manufacturing inaccuracies, especially the possible presence of thin bonding layer material on the top and bottom metallic walls. FR4-based bonding material can be lossy at such frequencies and increase the overall transmission loss through the structures.



(a) (b)

Fig. 6. Measurement results. (a) $|S_{11}|$ Magnitude. (b) $|S_{21}|$ Magnitude.

IV. CONCLUSION

We have presented a novel waveguide structure for low-loss antenna feed system at microwave and millimeter-wave frequencies. Simulation and measurement results show a good agreement, and the resulting waveguides represent a promising transmission-line medium that can be used for complex antenna feed and beam forming networks.

In the immediate near development and characterization of such structures, important issues such as end-connector de-embedding must be taken into account in order to have a loss estimate for the waveguide structure alone. The authors will have a more extensive discussion of these issues in a future journal paper.

V. ACKNOWLEDGEMENT

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