A Photonic Crystal Joint (PCJ) for Metal Waveguides

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***Abstract* — A novel method to eliminate currents in joints or interfaces in enclosed metal microwave structures is presented. By introducing a two-dimensional photonic crystal structure in the joint the conductor losses can be reduced to near that of a jointless structure. Experimental measurements at X-band of waveguide conductor loss using various joint geometries are presented, showing a drastic reduction in loss using the photonic crystal joint (PCJ). Various applications of the PCJ will be discussed, including H-plane waveguide joints, waveguide flanges and resonant cavities.**

I. Introduction

Closed metal structures (as opposed to planar or quasi-optical configurations) are still widely used at mm and sub-mm wavelengths, particularly for such components as oscillators, mixers, resonant cavities and directional couplers. Metal cavities can provide a low loss environment in which device embedding impedances can be predicted and controlled. Many state-of-the-art THz components rely on metal waveguides for their embedding environment. It appears that for the foreseeable future metal cavities will continue to play a crucial role, especially when one considers the advent of new micromachining capabilities for THz waveguide components [1]-[2].

When designing and fabricating metal cavities it is often convenient to fabricate the structure in several pieces, which can then be combined to form the final structure. This can simplify component fabrication and assembly, and also ease integration of devices into the structure. However, placement of joints or seams in the structure must be carefully considered because it can have a significant effect on the performance and loss.

Numerous methods have been developed over the years to minimize the effect of joints in metal microwave components. This paper describes a novel way to eliminate the effect of the joint, one that overcomes many of the disadvantages of previous methods. By introducing a two-dimensional photonic crystal structure (either metal or dielectric) into the plane of the joint, the currents are prevented from propagating into the joint, thus greatly reducing its influence on the microwave performance. The paper will first discuss the design and implementation of the photonic crystal joint (PCJ). Experimental measurements of conductor losses in X-band waveguide will be discussed, showing a drastic reduction in conductor loss using the PCJ. Applications of the PCJ will be discussed, including H-plane waveguide joints, waveguide flanges and resonant cavities.

II. PCJ Design and Fabrication

For a joint or interface placed arbitrarily in a waveguide structure there are, generally, currents flowing across the joint. These currents generate waves propagating into the joint, which are quickly attenuated by conductor losses, leading to additional loss in the structure. Also, resonances in the joint can produce spectrally sharp features in the device performance. By placing a photonic crystal structure in the joint, the fields in the joint can be suppressed over a wide frequency range, thus eliminating the effect of the joint.

There are a number of different ways in which the

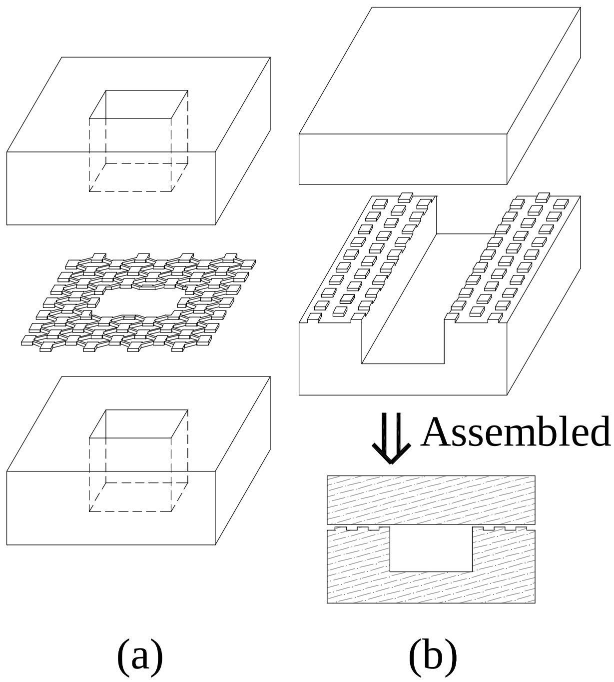

Fig. 1. Two techniques for implementation of the PCJ: (a) waveguide flange with PCJ formed by free-standing metal foil, and (b) waveguide joint with PCJ made of metal pillars formed on one piece.

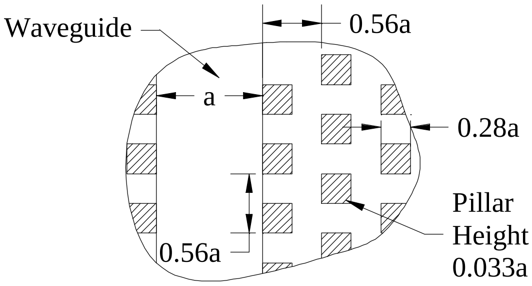

Fig. 2. Physical configuration of photonic crystal array.

photonic crystal structure can be introduced into the joint, including the placement of a free-standing dielectric and/or metal film in the joint (as pictured in Fig. 1(a)) or the fabrication of a periodic array of metal pillars on one surface of the joint (as pictured in Fig. 1(b)). For the second method the pillars can be formed by either direct machining or using photolithographic etching techniques.

The basic principals and design techniques for these photonic crystal structures (which in the metal pillar case is effectively a waffle-iron filter) are discussed in numerous references, e.g. [3,4]. For this research, the basic design methodology is to make a periodic 2-d array of reflecting elements with $\lambda/4$ periodicity at the center wavelength. The photonic crystal structure acts to prevent to flow of power in the split in any direction, which is crucial to the suppression of joint currents over a large bandwidth.

Simulations of the waveguide structure with the PCJ were performed using Ansoft-HFSS. The goal of the simulations was to determine the proper crystal geometry and periodicity to block joint currents over the full waveguide band. The crystal geometry first chosen, consisting of an array of square pillars, is shown in Fig. 2. The simulations predicted full waveguide band performance for this array. The height of the pillars was not crucial, and a gap between the pillars and the covers had little effect on performance up to a critical gap distance. Finally, several other crystal array configurations (not discussed here) were predicted to provide similar performance.

For the design described here, if the waveguide width is a, then the optimum periodicity was $0.56a$ for square pillars with side lengths of $0.28a$. The rows are staggered with respect to each other by half a period. For the X-band design, the pillar sides were 6.4 mm long, the spacing between pillars was 6.4 mm, and the pillar height was 0.75 mm. The metal pillars were formed by standard milling techniques.

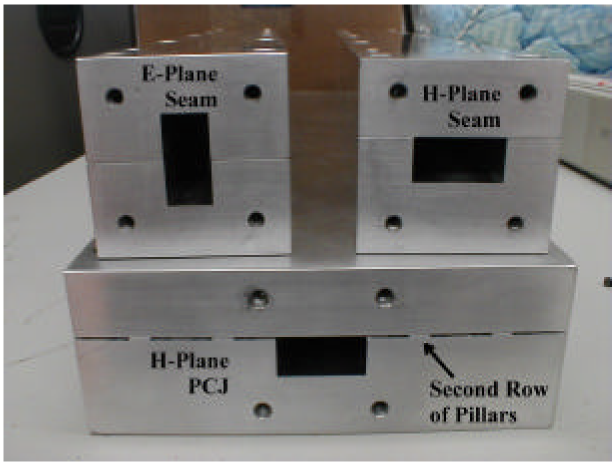

Fig. 3. Photograph of the Aluminum waveguide sections measured during this research.

III. Experimental Measurements of Waveguide Conductor Loss

Measurements of the conductor loss for X-band rectangular waveguide with various joint geometries were performed in order to provide experimental demonstration of the efficacy of the PCJ. The joints measured during this research were: 1) an E-plane joint, 2) an H-plane joint, and 3) an H-plane joint with a photonic crystal structure. A photograph of the three waveguides tested is shown in Fig. 3. The pieces were machined from Aluminum.

For the E-plane joint, shown in Fig. 4(a), the joint is a magnetic wall, and the currents in the waveguide walls do not cross the joint. The conductor losses for this case will therefore be very close to that of the jointless case. For the H-plane joint, shown in Fig. 4(b), the currents in the waveguide wall must cross the joint, exciting waves down the joint and causing generally increased conductor loss. For the H-plane joint filled with a photonic crystal structure the currents still flow across the joint, but propagation into the joint is suppressed. The losses for this case are predicted to be close to those in the jointless case, although slightly higher since the fields evanesce into the first several rows of the crystal.

In order to compare the measured losses with theoretical predictions, the ideal conductor loss for the X-band waveguide was calculated using the standard perturbation approximation [5]. However, it was assumed that physical factors such as surface roughness and work hardening [6,7] will increase the loss, and so the theoretical conductor loss was multiplied by a factor of two.

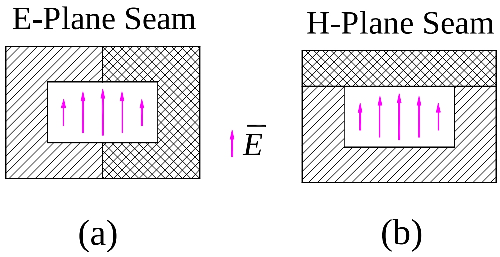

Fig. 4. Schematic of (a) E-plane and (b) H-plane joints in rectangular waveguide.

Measurements were performed at X-band (8.2 GHz to 12.4 GHz) on an HP 8510 Vector Network Analyzer. A TRM calibration was used in a two-port measurement scheme. As shown in Fig. 5, the E-plane joint was measured to have nearly the same loss as jointless rectangular waveguide in the “rough” limit described above. This low loss performance was found to hold even if the two halves were pulled apart leaving a large gap in the joint, as shown in Fig. 6.

The case changes dramatically when the joint is moved to the H-plane. With a gap between the halves of the structure significant power is coupled into the joint, and the loss depends on the termination of the joint. A typical result for the H-plane split with a 50 µm gap is shown in Fig. 5, demonstrating the drastic increase in conductor loss for this case. Interestingly, even with the gap in the H-plane joint reduced to zero the conductor loss is still considerably larger than the E-plane case. Physical inspection of the gap under magnification did not reveal any physical gap, and indeed, the pieces appeared to be in good contact. Also, for the “zero” gap case the joint termination had no effect on performance, as shown in Fig. 6. One possible explanation for this behavior is that the presence of a native oxide layer in the split sets an effective minimum gap thickness for the joint.

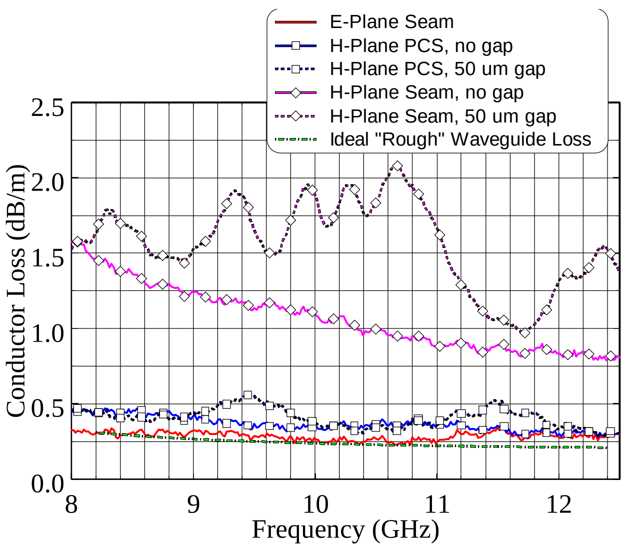

Fig. 5. X-band measurements of conductor loss for various waveguide joint configurations.

The measurements of the H-plane joint with a photonic crystal structure show a dramatic change relative to the case without this structure, as shown in Fig. 5 and Fig. 6. Even with sizable gaps between the pieces the conductor loss remains close to the ideal loss. The simulations were found to match the measured data quite well, particularly in determining the PCJ operational bandwidth.

Finally, although it may appear in Fig. 3 that the PCJ requires the waveguide piece to be prohibitively large, simulations indicated that nearly identical performance could be obtained using only the first 2 rows of pillars (see Fig. 3), thus making the size comparable with the other joint methods.

IV. Other Applications of the PCJ

This section discusses other applications of the PCJ for mm and sub-mm wavelength components.

A. Resonant Cavities

By using a PCJ with a resonant cavity type structure, it is possible to make the assembly and re-assembly of the cavity simpler and more repeatable, since no pressure or gasket is required to mate the pieces, and even a gap in the halves can be tolerated. One interesting possible application might be the fabrication of high-Q waveguide resonant cavities that can be quickly disassembled to allow introduction of material into the cavity. Another interesting potential application is the use of a PCJ to seal a Wheeler Cap [8], a device used to measure the efficiency of antennas. The use of a PCJ could greatly simplify the use of the Wheeler Cap, making

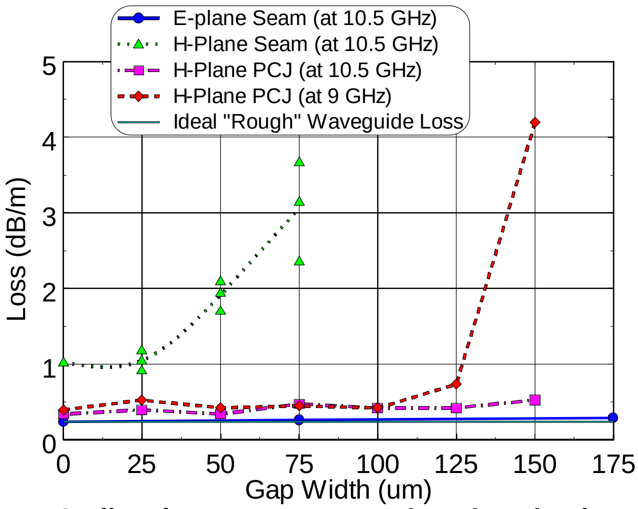

Fig. 6. Effect of gap in joint on waveguide conductor loss for X-band waveguide. The spread in the H-plane joint data shows the effect of joint termination on performance.

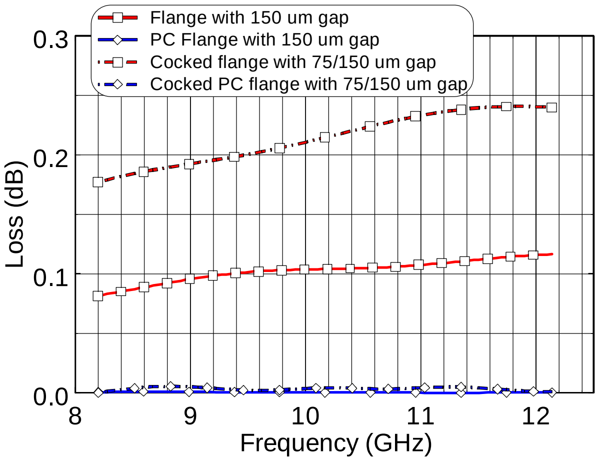

Fig. 7. Ansoft-HFSS modeling of waveguide flange with and without photonic crystals placed in the joint.

measurements more rapid and repeatable.

B. Waveguide Flanges

Numerous techniques have been developed to reduce the effect of waveguide flanges on waveguide performance. The placement of a photonic crystal structure in the flange interface can greatly improve the performance of waveguide flanges. The photonic crystal structure can be formed as a free-standing mesh, as shown in Fig. 1(a), or machined/etched on one surface of the flange interface. Ansoft-HFSS simulations were performed on a waveguide flange using a PCJ, the results of which are shown in Fig. 7. The simulations indicate that the PCJ flange has much greater tolerance to flange gaps than a simple mating flange. Also of interest is the immunity of the flange to cocking (see Fig. 7), something that can cause significant problems in both regular flanges and in choke flanges [5]. One application of the PCJ flange is to replace complicated alignment fixtures such as that described in [9], thus allowing precise, quick and very repeatable measurements. Another possible application is for the creation of a thermally isolating flange, e.g. see [10], since low insertion loss can be achieved even with a gap present between the two pieces.

VI. Conclusion

The PCJ provides a novel way of eliminating the effect of joints and interfaces in metal waveguide structures. Measurements of X-band waveguide have shown a drastic reduction in waveguide loss using the PCJ. The use of PCJ in other microwave structures such as resonant cavities and for waveguide flanges promises to allow improved performance as well as simplified and more repeatable assembly and testing. The flanges can be quite easily formed either by machining or photolithographic techniques. The PCJ is a novel and interesting new element for use with mm and sub-mm components and cavities, particularly with the advent of new micromachining techniques currently under development.

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