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LOW LOSS METAL DIPLEXER AND COMBINER BASED ON A PHOTONIC BAND GAP CHANNEL-DROP FILTER AT 109 GHz

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Abstract—In this paper, we present the design, fabrication and measurements for a W-band metal Photonic Band Gap (PBG) Channel-Drop Filter (CDF) diplexer, which can also be employed as a combiner to combine signals of different frequencies into a single waveguide. A PBG CDF is a device that allows channeling of a selected frequency from a continuous spectrum into a separate waveguide through resonant defects in a PBG structure. A PBG CDF transmits straight through all the frequencies except for the resonant frequency, and thus it represents a diplexer. Reversing the wave flow directions causes it to combine signals of different frequencies from two different waveguides into a single channel, representing a combiner. The device is compact and configurable and can be employed for mm-wave spectrometry with applications in communications, radio astronomy, and radar receivers for remote sensing and nonproliferation. High ohmic losses in metals constitute the main challenge in realization of a metal CDF at W-band. To mitigate the problem of ohmic losses, the filter was designed to operate at coupled dipole resonant modes instead of coupled fundamental monopole modes. The experimental samples were fabricated in two different ways: by conventional machining and by electroforming. The comparative results of the samples' testing are presented in the paper. Frequency selectivity of 30 dB with a 0.3 GHz linewidth at 108.5 GHz was demonstrated. In addition, we suggest an experimental method to check the frequencies of separate resonant cavities of fabricated samples which do not properly operate and a possible way to adjust the geometry of the cavities for the frequencies to meet the required specifications.

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1. INTRODUCTION

Performing separation and analysis of millimeter-wave spectra is essential for a broad range of applications. Presently the millimeter-wave band attracts more and more commercial interest, and consequently there is an evident need for novel or improved components to fully harness the millimeter-wave spectrum. In particular, components like multiplexers and combiners are needed to allow expansion of an extremely crowded RF spectrum towards millimeter-waves for military and civil communication applications [1]. Among the most important applications are intersatellite communications, broadband communication networks, microwave imaging, and radiometry [2]. The increasing demand for frequency locations with high bandwidth to satisfy the growing satellite communications applications makes it necessary to explore higher and higher frequency ranges. W-band (75–110 GHz) may be considered the new frontier of satellite communications [3], offering high data rate throughput at high altitudes and in space, where the wave attenuation is low. The 71–76 GHz/81–86 GHz segments of the W-band have already been allocated by the International Telecommunication Union to satellite services [4], although no commercial project has yet been implemented in these segments. Increasing spectrum occupancy at lower frequencies will eventually force commercial satellite operators to move to W-band.

We have initiated a project at Los Alamos National Laboratory (LANL) to construct and test a novel millimeter-wave passive multiplexer based on the photonic band gap [5] channel-drop filter [6] diplexer. A practical millimeter-wave multiplexer must be low-loss, wide-band, compact, easy to operate, and configurable to adapt to requirements of the mission. Due to high loss and challenging manufacturing of conventional low frequency waveguide diplexers with irises, the multiplexers currently available at millimeter-wave frequencies are primarily millimeter-wave dispersive gratings or dispersive prisms [7, 8]. There is also ongoing research on quasi-optical metal cavity diplexers for high-power applications [9–11]. The main disadvantage of quasi-optical systems is their bulkiness and sensitivity to thermal expansions and mechanical vibrations. For space and aircraft applications the system must be robust, compact and lightweight. A PBG channel-drop filter-based device has the potential to satisfy these requirements and become a unique, ultra-compact, configurable and easy-to-operate millimeter-wave passive diplexer. Diplexers stacked in series will compose a multiplexer.

The photonic band gap channel-drop filter was first proposed by Fan et al. [6]. A CDF is a device which is capable of extracting a certain frequency from a continuous spectrum in the bus channel to the detector channel. The rest of the spectrum is transmitted unaffected in the bus channel, thus making the CDF attractive for using as a resonant diplexer at millimeter-wave frequencies. Multiple designs of the channel-drop filter have been developed over the years [12–14], and many have found experimental verifications and applications at optical frequencies [14–16]. It was also proposed that PBG structures, or photonic crystals, may be advantageous to use for the guiding of millimeter-waves [17–20]. However, the actual filtering of millimeter-waves with a PBG CDF has never been experimentally verified. At LANL, we adapted the concept of the PBG CDF to millimeter-wave frequencies and demonstrated a dielectric CDF operating at around 240 GHz [21–23]. The dielectric CDF can be easily scaled to higher frequencies, up to 1 THz. However, for frequencies below 200 GHz, fabrication of the dielectric PBG CDF becomes challenging. Therefore, we came up with a new metal design of a channel-drop filter operating at a higher-order mode, which is scalable in the frequency range of 50 GHz to 200 GHz. The particular configuration of a PBG CDF-based diplexer operating near 109 GHz was built and tested in our mm-wave laboratory. This paper reports its design and the results of the tests.

2. DESIGN OF THE CHANNEL-DROP FILTER

The idea of a PBG CDF filter relies on the intrinsic property of two-dimensional photonic band gap structures to form band gaps, which are ranges of frequencies where the electromagnetic waves cannot propagate through and are reflected [24]. If a point defect is introduced into the PBG structure, then a certain frequency within the band gap will resonate, and thus it will be allowed to propagate through the defect. This property is exploited to create CDFs which employ two point defects to allow certain frequencies to transmit with little or no reflection in between two waveguides in a PBG structure.

Our design of the CDF, which was initially reported in [22], is based on a PBG structure which represents a square lattice of copper rods (Figure 1(a)). The filter consists of two parallel photonic crystal waveguides, which are the defects in the lattice in the form of rows of removed rods. Regular WR08 metal waveguides can be connected to the PBG waveguides, and the power will transmit from one waveguide into another. The two PBG waveguides are coupled by two micro-cavities. The cavities can be formed by either altering the size of rods [6] or by removing several rods from the structure altogether. In our early designs we removed only one or two rods to create small cavities supporting the fundamental mode. We quickly discovered, however, that once we introduced ohmic loss into the simulation, the resonances in those cavities became very broad. This was due to the fact that the ohmic quality factor of the cavities with fundamental modes was much smaller than the external quality factor due to the mode leakage from the cavity into the waveguides through the PBG structure. For the proper operation of the filter the ohmic quality factor must be much bigger than the external quality factor. In our final design, we removed four rods for each cavity (Figure 1(a)). In this case, each cavity supports two dipole-like modes at the frequency of 109 GHz. The dipole-mode cavity has a bigger volume than a monopole-mode cavity for the same frequency that consequently leads to much lower ohmic losses and a much higher ohmic quality factor.

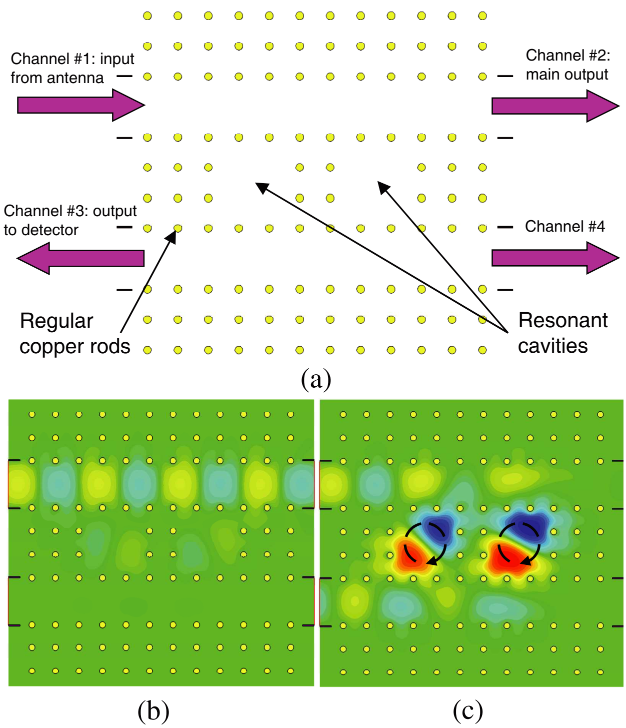


Figure 1. (a) Schematic of a channel-drop filter. (b) Electric field amplitude for the nonresonant frequency. Power transmits straight into channel #2 for nonresonant frequencies. (c) Electric field amplitude for the resonant frequency. The field pattern rotates in the direction of the arrows. At resonance the power transmits into channel #3 through the resonant cavities.

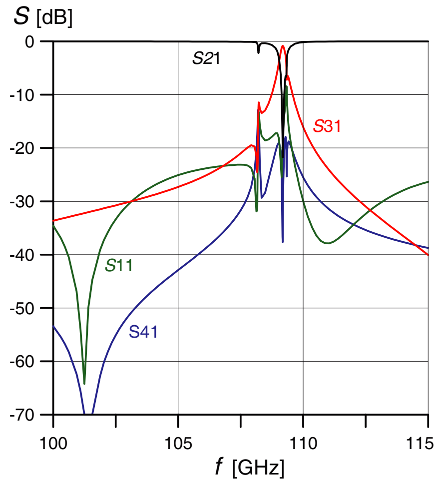


Figure 2. Simulated transmission through the channel-drop filter. Resonant frequency is 109 GHz.

The final design of our CDF structure operates in the following way. At the nonresonant frequency all the power goes to the main output (Figure 1(b)). At the resonant frequency the cavities are excited and the power goes to the detector output (Figure 1(c)). The simulated transmission characteristics of the filter are shown in Figure 2. Simulations were performed with CST Microwave Studio [25].

Each micro-cavity supports two resonant dipole modes, one with the field variation in the direction across the waveguides and one with the variation in the direction along the waveguides. The incoming wave from channel #1 excites four normal oscillations of this two-cavity system, which are symmetric and anti-symmetric combinations of partial modes (Figure 3). The frequencies of all of these oscillations are generally different. For the proper operation of the filter, two of the oscillations, one of which is a symmetric and the other one is an anti-symmetric combination of partial modes (patterns (a) and (c), or patterns (b) and (d), or patterns (a) and (b), or patterns (c) and (d) in Figure 3), must be degenerate in both frequency and external Q-factor and must be excited by the incoming wave. Also, in the real-life system, the ohmic Q-factors of the oscillations must be much smaller than their external Q-factor related to radiation into the waveguides.

If the incident wave is of the proper frequency and has a favorable phase advance on the distance in between the two micro-cavities to excite the oscillation pattern 3(a), then it will also excite the oscillation pattern 3(b), as these oscillations have the same distance along the

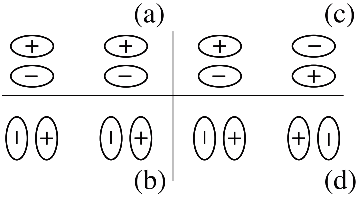


Figure 3. A schematic of all the normal modes of a square cavity in a PBG structure.

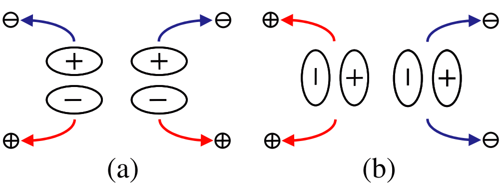


Figure 4. Illustration of the phase relations between the waves radiated by the two normal oscillations of the PBG cavities.

input waveguide between the field peaks of the same sign. Similarly, the wave that excites the oscillation pattern 3(c) will also excite the 3(d) pattern. However, the oscillation 3(b) will be delayed in phase by a quarter wavelength in comparison to the oscillation of 3(a). Therefore, the resulting field pattern of the excited oscillation will rotate clockwise as shown in Figure 1(c). The same is true about the patterns 3(c) and 3(d).

Each of the two normal oscillations radiates forward and backward into the PBG waveguides with equal magnitudes (Figure 4). In our design of the filter, we would like all the power at a certain frequency to go into the detector channel #3. In order to achieve that, the fields radiated by the two normal oscillations must effectively interfere with each other to add up in phase in channel #3 and cancel each other in channel #4. It may happen only if the frequencies and the Q-factors of two normal oscillations are equalized [6]. When the frequencies of normal modes of choice are close, frequency degeneration can be achieved by adjusting the two different coupling mechanisms between the two micro-cavities: one of them is through the waveguides, and the other one is directly through the PBG structure. These two mechanisms may split the frequencies in between two normal modes in different directions: one increases the frequency of the symmetric mode and reduces the frequency of the anti-symmetric mode, and the other mechanism does the opposite. The proper choice of vertical and horizontal spacings between the rods forces two frequency splits to equalize the frequencies of the normal oscillations. The couplings of normal oscillations to the input wave (which determine the Q-factors) may be adjusted by the proper choice of the distance between the micro-cavities and their dimensions (number of missing rods). The value of the frequency transmitted into channel #3 may be adjusted by varying the diameter of the rods in the structure.

From the mode symmetry it follows that waves radiated into the waveguides by the oscillation pattern 3(a) (the same as 4(a)) have the opposite phases in the upper and lower waveguides. However, waves radiated by the oscillation pattern 3(b) (the same as 4(b)) have the same phases in the upper and lower waveguides, but different phases in the left and right directions. As a result of this phase relation, when two oscillations co-exist at the same frequency with the same magnitude of radiated waves due to equal Q-factors, the waves going in the directions of channels #1 and #4 are all canceled, and the waves going in the directions of channels #2 and #3 are added in phase. The phases of waves radiated by both the pattern 3(a) and the pattern 3(b) are exactly opposite to the input wave phase due to the excitation condition, so that radiation into channel #2 is canceled by interference with the incident wave. Therefore, in the absence of losses, the whole power at the resonance frequency goes directly into the test output channel (channel #3) (Figure 1(c)).

At all other (nonresonant) frequencies, the power from the input waveguide, channel #1, exits directly into the main output waveguide, channel #2. Channel #4 is a test channel; no power should transmit into channel #4 at any frequency. Placing a receiver at the resonant output, channel #3, provides an opportunity for analyzing the signal at the corresponding single carrier frequency of interest. Multiple CDFs with different frequencies can be stacked in series, and this system will act as a multiplexer. Reversing the wave propagation directions will result in combining of signals at different carrier frequencies from different sources into a single channel.

The proof-of-principle CDF device was designed with CST Microwave Studio [25] with the parameters listed in Table 1 to operate at the frequency of 109 GHz. The choice of frequency was mostly determined by the simplicity of fabrication. Simulated S-parameters of the filter are shown in Figure 2. The diplexer transmits almost 100% into channel #2 at all frequencies, except for the frequencies close to the resonant frequency of 109 GHz. At 109 GHz 90% of power is dropped into the detector channel #3 and almost 10% goes to ohmic loss. The transmission into channel #3 at 109 GHz is 30 dB above

Table 1. Design parameters of the 109 GHz CDF.

Material of the rods	copper
Diameter of the rods	0.25 mm
Spacing between the rods	1.02 mm
Width of the PBG waveguide	2.03 mm
Height of the structure	1.02 mm

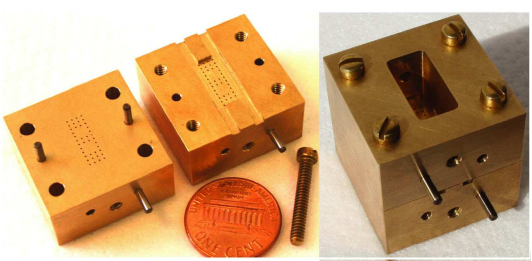
the background and the line-width is 0.3 GHz. Two smaller distinct spikes in Figure 2, one slightly above 109 GHz and one slightly below, correspond to excitation of the two other normal oscillations of the cavities.

3. FABRICATION AND TESTING OF THE CLAMPED DEVICE

For the purpose of the proof-of-principal experiment, the device was further simplified for fabrication by replacing the PBG structure at the top and bottom of the device with solid metal walls

The first experimental sample was fabricated in the following way. A solid copper cube with 1 inch sides was cut into two blocks. Two pocket dips were machined into each block and a structure of holes was drilled inside each of those dips. Two regular WR08 waveguides and a rectangular opening for the filter were machined on the other side of one of the blocks (Figure 5(a)). The two pieces were connected together with precision pins and screws (Figure 5(b)). An array of copper rods was prepared by straightening copper wire with the diameter of 10 thousands of an inch. Precision tweezers were used to insert the rods through the holes in the copper blocks to form the PBG structure of the filter. All parts were thoroughly cleaned in an ultrasonic bath before the assembly

Special WR08 waveguide splitters were fabricated and connected to the assembled device on each side. The two outer ports of the splitters were connected to the Network Analyzer to perform the testing, and RF loads were installed on the two other ports



(a) (b)

Figure 5. Photograph of the copper block with holes and waveguides for the channel-drop filter and scale. (a) The top and bottom halves of the block are shown separately. (b) The top and bottom halves of the block are connected together with screws.

(Figure 6). Our Network Analyzer system was composed of WR08 Oleson Microwave millimeter wave test heads driven by an Agilent HP8510C Network Analyzer.

The main disadvantage of this fabrication method was loose connection between the filter body and the rods. Some rods could even fall out when the copper block was moved. This system gave us an opportunity, by replacing the rods of the structure during the course of the experiment, to tune the filter for the maximum transmission

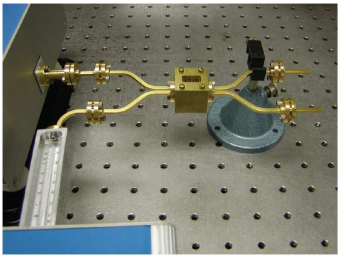


Figure 6. Photograph of the measurement set-up in the mm-wave laboratory.

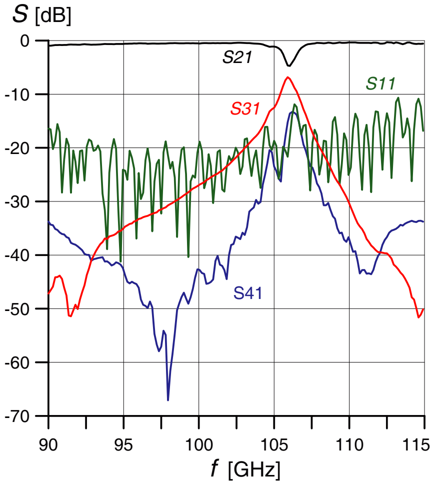


Figure 7. Measured transmission through the channel-drop filter made by conventional machining. Resonant frequency is 106.5 GHz.

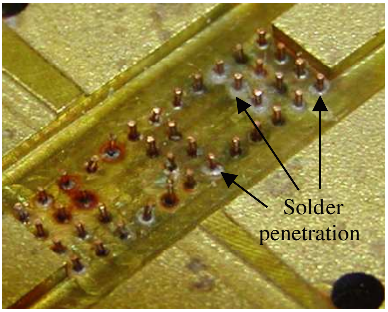


Figure 8. Photograph of the channel-drop filter with soldered rods. The filter is cut apart with electro-discharge machining. Solder penetration from the outside is clearly visible.

into channel #3, as all rods were slightly different in straightness and thickness. However, we were unable to fine-tune the sample for close to 100 percent transmission of the signal into the detector channel #3 at the resonant frequency (Figure 7). In our best tuned sample, the channeled frequency was measured to be 106.5 GHz and was red-shifted in comparison to the design value. The signal at the detector channel was attenuated by 6 dB, and the signal at the main output (channel #2) at resonance was attenuated by less than 5 dB. The excessive ohmic loss (estimated to be at about 30 per cent at resonance) prevented theoretical wave cancelation of transmission into the main output channel #2 due to insufficient radiation from the normal modes excited in micro-cavities as explained in Section 2, making it impossible to properly tune the filter. In spite of the high losses the selectivity in the detector channel was greater than 35 dB. We reasoned that poor electrical connections of the rods to the copper block were the main source of the observed loss.

To solidify the system and reduce the losses, we tried soldering the inserted rods from the outside of the device. Soldering reduced the loss but at the same time it detuned the device. We cut the filter in two halves with a wire electrical discharge machine and discovered that some solder material had penetrated inside of the micro-cavities and resulted in detuning (Figure 8).

4. FABRICATION AND TESTING OF THE ELECTROFORMED DEVICE

The second sample was fabricated via electroforming by Custom Microwave, Inc. in Longmont, CO, USA. A PBG structure consisting of rods sandwiched in between two half-millimeter thick plates was electroformed as a single copper part, so that a good electrical connection between the rods and the plates was automatically ensured. Some copper was also deposited to form sidewalls for the two WR08 waveguides at each side. The final device is shown in Figure 9. A special containment box and waveguide splitters were manufactured separately and served to connect the device to regular WR08 waveguides for power input and output (Figure 10).

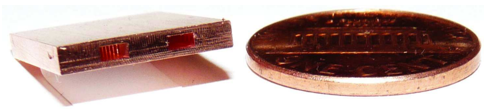


Figure 9. Photograph of the electroformed channel-drop filter and scale.

Two electroformed samples were fabricated and tested in a millimeter-wave laboratory. Two out of the four waveguide ports were connected to the WR08 Oleson Microwave millimeter-wave test heads, and RF loads were installed on the other two ports, similar to the setup of Figure 6. Much lower ohmic loss was observed in the electroformed sample, as expected. The measured S-parameters for the first sample were in excellent agreement with the design (Figure 11). The signal at the detector channel #3 was higher than -3 dB at the resonant frequency with the background level lower than -30 dB. The measured resonant frequency was 108.5 GHz, which is very close to the design frequency of 109 GHz.

However, when the second sample was measured, it was discovered that the transmission into channel #3 at resonance was -5 dB, and

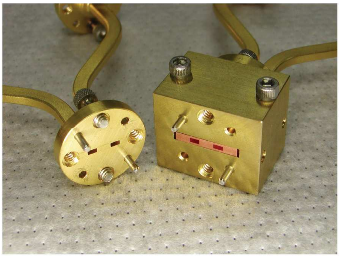


Figure 10. Photograph of the electroformed CDF placed into a containment box with the attachable input/output waveguides.

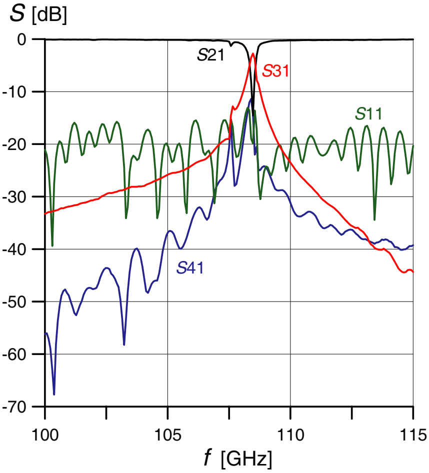


Figure 11. Measured transmission through the channel-drop filter made by electroforming. Resonant frequency is 108.5 GHz.

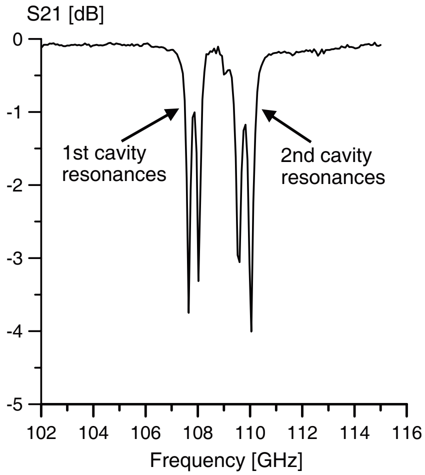


Figure 12. Measured transmission through the electroformed CDF with one cavity detuned by a copper rod inserted in the center. Four dips correspond to the filter resonating in each of the four partial eigenmodes of the two micro-cavities.

there was also a significant transmission into channel #4 and reflection back to channel #1 at the resonant frequency. This result may be easily explained. Both samples were manufactured with the standard manufacturing tolerance of 0.025 mm (one thousandth of an inch). We demonstrated in simulation that if the position of the rods in the structure is randomly shifted by 0.025 mm, then the filter becomes completely detuned and transmission into the test channel #3 is notably lowered. The reason for it is that the frequencies of the partial modes of the two micro-cavities become different (further apart than the linewidth of the resonance) and the efficient interaction of the cavities becomes impossible. Therefore, we were required to develop a method to tune the partial frequencies of the micro-cavities.

First, for the purpose of diagnostics, we drilled two throughholes through the middle of each micro-cavity; each had a diameter of 0.25 mm (10 thousandths of an inch). A copper rod was inserted in turn into each micro-cavity through the holes to shift the resonant frequencies from those of the other cavity, allowing us to measure the frequencies of the partial modes in the other micro-cavity (Figure 12). It was discovered that the frequencies of the partial modes in the one micro-cavity were about 250 MHz lower than the frequencies of the partial modes of the second micro-cavity.

We decided to tune the sample following the acid-etch technique that was successfully implemented by the authors of [26]. The technique was developed to selectively adjust the diameters of copper rods in a 17 GHz copper PBG accelerating structure. Jack-o-lantern candles were melted in a beaker on a hot plate and were supposed to serve as a masking material for the micro-cavity which was low in frequency. This wax was found to be suitably resistant to chemical attack by the acid solution. The structure was dipped half way in molten wax which was about as viscous as water, so that its lower half, including one micro-cavity, was covered with wax. Acid solution was mixed as follows: 100 ml nitric acid, 275 ml phosphoric acid, 125 ml acetic acid. The structure was immersed in this solution at 45° with the intent of removing 0.0025 mm (0.0001 inch) per 55 seconds from the copper rods, making them thinner. Finally, the wax was removed with a detergent cleaner in an ultrasonic tank at 70°C. The structure was rinsed with deionized water, dipped in chromic acid solution for final cleaning of tarnish spots from the previous steps, rinsed in deionized water again and dried. However, when tested, no significant change in frequency of the etched micro-cavity was observed. We then repeated the etching process and realized, after careful observation, that no acid actually went into the structure, because the structure's dimensions were much smaller than those in [26], and the geometry was also different. Thus, air was trapped inside of the PBG filter, preventing penetration of the acid.

We discovered, however, that if the structure with no masking wax was dipped into the acid, then air did not get trapped, and both micro-cavities got etched at the same time. Therefore, the developed tuning procedure is still applicable for tuning the overall channeled frequency of the operational filter. We were able to lower the channeled frequency of the sample by as much as 1 GHz using this procedure.

Later, the second sample was cut in halves with electrical discharge machining. We did not see any evident reason for why this filter was detuned. Apparently, detuning was due to the slight differences in the diameters and positions of the rods surrounding the two micro-cavities.

5. CONCLUSION

We have successfully designed, fabricated and tested a low loss copper diplexer and combiner based on a photonic band gap channel-drop filter at W-band. Several samples were fabricated. The clamped samples confirmed the theory but demonstrated high losses. The sample that was fabricated via electroforming demonstrated low loss and transmission characteristics that were very close to the design. The frequency of 108.5 GHz was filtered into the test channel with a less than 3 dB attenuation. The filter showed a frequency selectivity of more than 30 dB and a line width of approximately 0.3 GHz (Figure 11). An idea of tuning the transmitted frequency with etching was experimentally verified.

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