

Article

Waveguide-Based Split-Ring Resonators for Narrow-Band Filters Near 380 GHz

Samantha Leigh Williams and Steven C. Reising *

Electrical and Computer Engineering Department, Colorado State University, Fort Collins, CO 80523, USA; samw97@colostate.edu

* Correspondence: steven.reising@colostate.edu

Abstract: This work addresses the design of sub-terahertz narrow-band resonators for high performance and low-cost manufacturability. The intended application for these resonators is to realize narrow-band filters for passive millimeter-wave sounding of upper atmospheric humidity using the 380 GHz water vapor absorption line. Various narrow-band resonator designs and manufacturing processes were considered for this application. A design based on a waveguide split-ring resonator topology was selected to be developed and manufactured using laser machining. Experimental results are presented and compared with results from simulations for ten narrow-band resonators fabricated with a design center frequency in the WR-2.2 (325–500 GHz) waveguide band.

Keywords: millimeter-wave; terahertz; passive devices; remote sensing; narrow-band; split-ring resonators; radiometer; machining tolerances; CubeSats; small satellites



Citation: Williams, S.L.; Reising, S.C. Waveguide-Based Split-Ring Resonators for Narrow-Band Filters Near 380 GHz. *Electronics* **2024**, *13*, 2894. <https://doi.org/10.3390/electronics13152894>

Academic Editor: Christos J. Bouras

Received: 28 June 2024

Revised: 13 July 2024

Accepted: 16 July 2024

Published: 23 July 2024



Copyright: © 2024 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

1. Introduction

This work focuses on design and manufacturing considerations for narrow-band waveguide resonators in the upper-millimeter wave or lower-terahertz frequency range, at frequencies above 200 GHz. The intended application for these narrow-band resonators is for atmospheric remote sensing of water vapor from small satellites. The resonators are intended for operation near the 380 GHz water vapor absorption line. It is important to develop simple, low-cost, reliable passive component technology that operates above 200 GHz. Three topics will be addressed in this work: passive sounding of upper atmospheric humidity using the 380 GHz water vapor absorption line, manufacturing limitations of millimeter-wave components above 200 GHz, and incorporating a metamaterial-inspired split-ring resonator design in the WR-2.2 waveguide band. This work validates the use of a waveguide-based split-ring resonator for narrow-band sensing of water vapor profiles in the sub-terahertz band, near the 380 GHz absorption line. The work also validates the use of the laser machining process using thin metal sheets for use in the sub-terahertz band.

The remainder of the paper is organized as follows: Section 2 provides a brief background on the three topics relevant to this work. Section 3 considers existing designs for sub-millimeter wave and lower-terahertz resonators. Section 4 presents the resonator design parameters, and Section 5 discusses resonator manufacturing techniques. The results are presented in Section 6, and Section 7 provides a summary and the conclusions of this work.

2. Background

2.1. Remote Sensing Applications of Narrow-Band Resonators

This work focuses on the development of compact, passive narrow-band resonators in the upper-millimeter wave or lower-terahertz frequency range. In atmospheric remote sensing applications, radiometers at higher frequencies/shorter wavelengths than microwave or millimeter-waves are needed to obtain new information about the upper troposphere

and lower stratosphere (UTLS). Climate models are currently limited by a lack of knowledge of properties of clouds in the UTLS [1–3]. Climate change predictions are currently limited by uncertainties in cloud properties and processes. To improve these predictions, improved estimates are needed of both the size of ice particles in the upper troposphere and vertical profiles of water vapor and atmospheric temperature [1,2].

Traditionally, global, all-weather atmospheric sounding measurements from space are performed at microwave and millimeter-wave frequencies below 200 GHz [3]. Observations at upper-millimeter-wave and lower-terahertz frequencies can provide additional information at higher atmospheric altitudes, as well as sensitivity to smaller ice particles. In addition, these observations offer improved horizontal spatial resolution, providing more accurate information, complementary to currently available observations that provide coarser resolution at lower atmospheric altitudes.

One example of an upper-millimeter-wave and lower-terahertz radiometer is the Tropospheric Water and Cloud Ice (TWICE) instrument. TWICE was developed in collaboration among the Microwave Systems Laboratory at Colorado State University, the Jet Propulsion Laboratory, and the Northrop Grumman Corporation. TWICE was developed with the objective of improving the current understanding of the role of ice clouds in the Earth's climate [1,2]. The instrument utilizes low-noise amplifier (LNA) technology based on InP high-electron-mobility transistors (HEMTs) with both 35 nm and 25 nm gate lengths that were customized specifically for remote sensing of the Earth's atmosphere [4]. These low-noise amplifiers provide substantial gain with sufficiently low noise for remote sensing using sub-terahertz frequencies [5]. TWICE has direct-detection radiometer channels centered at 240 GHz, 310 GHz, 670 GHz and 850 GHz to retrieve ice cloud particle size information in the upper troposphere. A second example of an upper-millimeter-wave and lower-terahertz radiometer is the Smart Ice Cloud Sensing (SMICES) instrument. SMICES has direct-detection radiometers centered at 250 GHz, 310 GHz and 670 GHz to observe ice clouds. Both TWICE and SMICES also include a heterodyne receiver, yielding seven narrow-band channels near 380 GHz for water vapor sounding [6,7].

It is important to state that this scientific goal is attainable with heterodyne radiometer architecture by down-converting to intermediate frequencies well below 200 GHz. However, the direct-detection architecture significantly reduces the power consumption and noise figure [6] of the receiver, as well as system complexity, improving the measurements and reducing the resources needed to operate the radiometer. Future airborne and space-borne measurements in the upper-millimeter-wave and lower terahertz have the potential to improve the accuracy of climate change models by providing more information on the size of cloud ice particles, as well as on water vapor and temperature profiles in the upper troposphere [1,2]. It is necessary to develop compact, reliable passive components above 200 GHz to enable small satellites to extend the capabilities of passive measurements for atmospheric remote sensing.

The atmospheric remote sensing application in this work requires that the filters focus on a specific frequency range with narrow bandwidths. In general, the atmospheric absorption spectrum has a number of water vapor lines, including the 183 GHz, 325 GHz, 380 GHz, 448 GHz and 557 GHz. At the peaks of the water vapor lines the absorption is at a maximum but varies substantially with frequency, requiring narrow sensor bandwidths to obtain valuable information. However, at frequencies further from the peaks of the water vapor lines, the rate of decrease in the absorption is smaller, allowing for wider sensor bandwidths [8]. Sounding at higher altitudes can be performed using the 380 GHz absorption line. This specific application has chosen to use the 380 GHz water vapor line, with sensor bandwidths around 3–4%. The higher-frequency bands allow for sounding at higher altitudes, and can provide more information on ice clouds compared to the 183 GHz line. The bands higher in frequency have better spatial resolution than the lower bands, and the instrument would be able to measure regions where there are small or wispy clouds, increasing the probability of clear sky situations.

2.2. Manufacturing: Issues at Higher Frequencies

The design and manufacturing of waveguide components above 200 GHz pose several challenges based on current machining limitations. At frequencies below 200 GHz, waveguide structures are generally manufacturable using traditional machining technology. However, in the design of narrow-band waveguide filters at frequencies above 200 GHz, manufacturing tolerances and repeatability limit the ability to achieve the desired filter response due to the decrease in size of critical component dimensions with decreasing wavelength. Previous sub-terahertz remote sensing receiver designs have implemented narrow-band band-pass filters in split-block waveguides [9–15] using various machining processes. In most of these cases, it was found that the machining processes had caused undesirable variations in the filter response compared to the simulations. Two of these cases are described in further detail.

In the first case, a waveguide-based band-pass filter was designed for operation near 255 GHz and fabricated in an aluminum split-block waveguide using a micromechanical milling process [9]. The machining process caused the waveguide's measured response to have a significantly higher insertion loss than the simulation results. After measuring the fabricated filters' critical dimensions, the authors determined that the increased loss was due to the surface roughness of the material and loss per unit length of the waveguide [9]. This was verified through additional simulations.

In the second case, a narrow-band band-pass filter was designed and fabricated with a center frequency near 680 GHz [10]. The filter was fabricated in a copper waveguide using a 3D fabrication process providing a dimensional accuracy of $\pm 5 \mu\text{m}$. For this design, it was found that the center frequency of the machined design was an average of 5% lower than the intended design. Therefore, the second iteration for fabrication was intentionally designed to be higher in frequency to compensate for the machining variability [10].

The results of fabricated designs reported in [9–15] had variations in frequency response due to machining and material limitations. For this application, the filters need to be reliably machined at a low cost. We have additionally explored metamaterial filter designs in our work to overcome these issues.

2.3. Metamaterials: A Brief Introduction

As the design frequency increases above 200 GHz, many traditional, naturally occurring materials perform poorly due to increasing loss as the frequency increases, as well as limitations in manufacturing capabilities. Partly in response to this need, the new field of metamaterials emerged around the late 1990s and early 2000s to provide new capabilities to engineer the photonic response using sub-wavelength structures, rather than relying on the inherent electromagnetic response of materials. Typically, devices with photonic responses are implemented using periodic structures. However, engineered metamaterials require the development of new designs, commonly using patterns with sub-wavelength dimensions. These designs critically depend upon the physical geometry of the material structure [16]. Metamaterial design concepts were considered for this work for several reasons. First, alternative machining techniques are commonly utilized for metamaterial designs. Second, the purpose of the development of metamaterials is in part to address the need for the design of devices operating above 200 GHz. Third, this field is often utilized in the infrared and optical regime, so it may be promising for millimeter-wave/lower-terahertz applications above 200 GHz [17].

3. Sub-Millimeter Wave and Lower-Terahertz Resonator Designs

A number of sub-millimeter wave narrow-band band-pass filter designs have been developed and fabricated to date [9–15]. The key issues at sub-millimeter wavelengths are the narrow bandwidths and robustness to machining issues. Since the critical dimensions of these designs are of the same order of magnitude as the manufacturing tolerances, it is difficult to machine filters with narrow bandwidths reliably. Due to manufacturing tolerance limitations on the realization of waveguide filters above 200 GHz, alternative

designs have additionally been considered. Metamaterials have been investigated in this work to realize resonators appropriate for atmospheric remote sensing applications. Metamaterial designs have advantages over waveguide-based topologies due to their alternative manufacturing techniques, engineered dielectric properties, and the ability to achieve narrow resonator bandwidths.

The first metamaterial design concept considered for sub-terahertz narrow-band resonators was photonic crystals. Photonic crystals are periodic crystal lattice structures of atoms or molecules. The lattice structure can be designed to prohibit certain energies (or their corresponding frequencies) from propagating through the structure, i.e., “gaps” in the structure of the crystal [18]. A magnetically tunable band-pass filter was designed with a center frequency tunable over a 67 GHz range from 1.126 THz to 1.193 THz, while maintaining a 3 dB bandwidth narrower than 2 GHz [18]. This result demonstrated that it is possible to design tunable narrow-band metamaterial filters at terahertz frequencies.

The second metamaterial design concept considered for the sub-terahertz narrow-band resonators was the mesh filter. Wang et al. [19] designed a mesh band-pass filter near 300 GHz using an SU-8 material-based micromachining technique. The result was essentially a 0.3 mm thick array of mesh resonators. As the thickness of the mesh filter increased, the quality factor (Q) of the filters increased linearly, but the insertion loss increased dramatically due to material loss and alignment variations.

A third metamaterial design, the split-ring resonator, was first implemented as a waveguide-based resonator in 2016 in the WR-75 band (10–15 GHz) [20]. The split-ring resonator is traditionally implemented as a microstrip design. The design is not commonly found in rectangular waveguide filter designs. To the authors’ knowledge, Ref. [20] is the only known experimental implementation to date of a split-ring resonator design that was machined in a rectangular waveguide. Five complementary split-ring resonators (CSRRs) were designed, fabricated on an aluminum plate and measured with different split positions [20]. It was found that the position of the split in a single CSRR can change the fractional 3 dB bandwidth of the device over the range of 3.2 to 31%. Importantly, the CSRR design is significantly more compact in size than traditional microwave waveguide-based resonators, allowing it to be machined as a single part with a laser fabrication method.

4. Narrow-Band Resonator Design

Based on prior work discussed in Section 3, the CSRR resonator design was chosen for further study. Although [20] was fabricated at a significantly lower design frequency, this design has been traditionally fabricated in microstrip configuration for operation at frequencies higher than 373 GHz [20–24]. A waveguide inductive iris filter [9–11] was additionally designed for a first-order resonator design for comparison with the CSRR design. The waveguide inductive iris filter was chosen for comparison since it is commonly used in millimeter-wave remote sensing of the atmosphere [4–7,9–11]. The CSRR waveguide-based resonator design was chosen for its flexibility in bandwidth and simplicity in design [20]. This means that the filters need to be of low insertion loss and narrow bandwidth. In addition, the filters need to be compact in size and machined reliably with minimal variations to the critical dimensions of the resonator.

Based on the simulation results, sufficiently narrow filter bandwidths near 400 GHz can be achieved using either metamaterial or waveguide-based resonators. However, manufacturing processes must be considered for sub-terahertz filter components since there are significant practical challenges in obtaining both desired and repeatable frequency responses [9,10]. The cost of manufacturing the resonators increases with frequency since tighter tolerances are needed for smaller critical component features that scale with wavelength. Statistical analysis of simulation results aids in predicting machining results for each filter topology, as presented in this section.

4.1. Inductive Iris Waveguide Resonator Design

An inductive iris waveguide resonator was designed in an air-filled WR-2.2 (325–500 GHz) waveguide with standard interior dimensions of 0.57 mm by 0.285 mm. The waveguide inductive iris design was implemented as a single resonator, with the entire structure one wavelength in length. Simulation results yield a fractional bandwidth of approximately 0.5% (2 GHz).

4.2. CSRR Waveguide Resonator Design

A complementary split-ring resonator was designed in a WR-2.2 (325–500 GHz) waveguide using design equations from [21]. Simulation results yield a fractional bandwidth of approximately 3% (15 GHz). From (1), the CSRR design is heavily dependent on the guide wavelength at the desired center frequency. Simplified design equations for a single CSRR are shown to emphasize this point. The side length of the resonator can be calculated from the following:

$$\lambda_g/4 = S \quad (1)$$

where S is the side length of the CSRR square trace and the guide wavelength λ_g is:

$$\lambda_g = \lambda / \sqrt{\epsilon_r - (f_c/f)^2}. \quad (2)$$

Here, λ is the free-space wavelength at frequency f , f_c is the cutoff frequency of the WR-2.2 air-filled waveguide, and ϵ_r is the relative permittivity of the medium inside the waveguide. Using (1) and (2) and a center frequency of 373 GHz, the simulation results are shown in Figure 1, and a drawing of the CSRR design can be referenced in Figure 2. It is important to consider the thickness of the metal sheet used to realize the CSRR in the simulations. In [19], it was found that for thin sheet resonators, the loaded Q factor increases linearly with sheet thickness. This principle can be extended to the CSRR design. In general, as the sheet thickness increases, the loss will also increase. For this design, a sheet thickness of 200 μm was chosen based on commercially available thin copper sheet materials. Starting with this baseline, the design parameters were to yield the desired center frequency and bandwidth response.

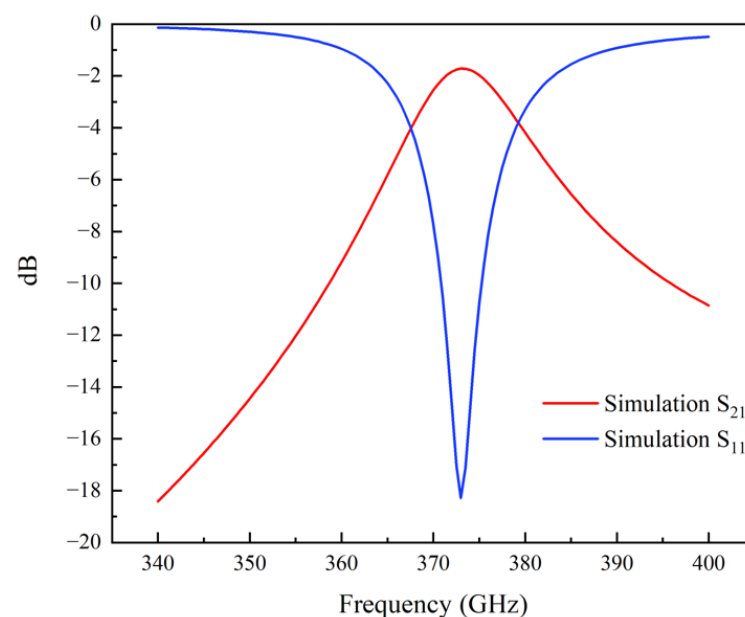


Figure 1. Simulated results for the CSRR design without a taper.

4.3. Variation in Critical Dimensions

The CSRR waveguide resonators were designed and simulated using variations in critical dimensions to represent machining tolerances within a standard deviation of

25.4 μm (~ 1 mil). Statistical analysis was performed on the model results to determine the magnitude of the center frequency and bandwidth variations. Simulations were conducted for the inductive iris waveguide resonator design to provide a basis for comparison in this work.

First, a simulation study was conducted to evaluate potential limitations due to manufacturing for both waveguide iris resonators and metamaterial resonators. Simulations were performed for 1000 realizations of each resonator design, each one representing a possible manufactured variation within the specified 25.4 μm tolerance. For each realization, the critical dimensions listed in Table 1 were varied based on a Gaussian distribution with a standard deviation of 25.4 μm (~ 1 mil). The distributions were truncated in the simulation study to ensure physical and realizable bounds on the dimensions. Table 1 describes the effects of the variations in physical dimensions on resonator performance for the CSRR design shown in Figures 2 and 3. The four critical parameters for the CSRR trace that are subject to manufacturing variations are the split length, trace thickness, side length of the trace, and the split placement.

The bandwidth and center frequency distributions for 1000 realizations of the two designs are shown in Figure 3. The results for the inductive iris resonator designed with a center frequency of 373 GHz and 2 GHz 3 dB bandwidth are shown in Figure 3a. The results for the CSRR design with a center frequency of 373 GHz and 11 GHz 3 dB bandwidth are shown in Figure 3b. The inductive iris waveguide resonator provides a narrower bandwidth of 0.5%, as compared with 3% for the split-ring resonator. It is important to note that both designs are based on a single resonator. To achieve sharper band-pass responses, such resonators can be cascaded to realize multi-stage band-pass filters. The CSRR design was chosen for its greatly improved manufacturing yield and lower per-unit manufacturing cost.

Table 1. Critical dimensions for the CSRR design.

Dimension	Variation in Dimension	Bandwidth	Center Frequency	Insertion Loss
Split Length (L_s)	Increase	Increase	Increase	No Noticeable Correlation
Trace Thickness (t)	Increase	Increase	Decrease	Decrease
Side Length (S)	Increase	No Noticeable Correlation	Decrease	Decrease
Split Placement	Counter-clockwise or Clockwise	Increase	No Noticeable Correlation	No Noticeable Correlation

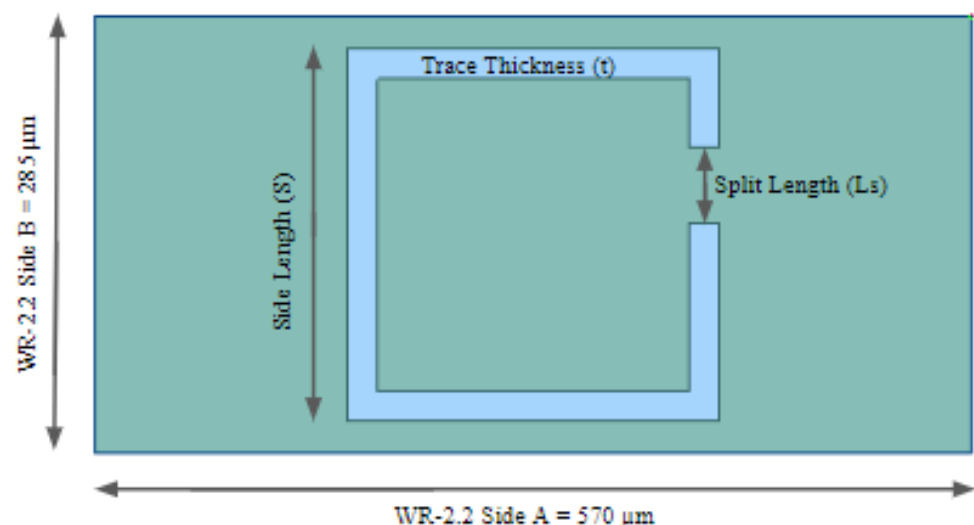


Figure 2. Complementary split-ring resonator design, showing dimensions of interest that are affected by machining tolerances.

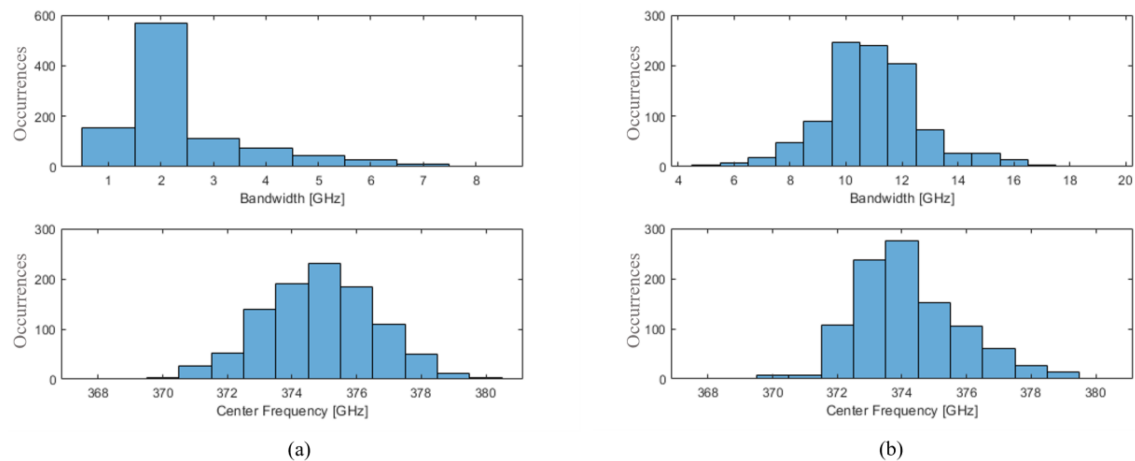


Figure 3. (a) Bandwidths and center frequencies of 1000 realizations of a simulated inductive iris waveguide filter, centered near the 380 GHz water vapor absorption line with a frequency offset of -7 GHz. (b) Bandwidths and center frequencies for 1000 realizations of a simulated complementary split-ring resonator filter centered near the 380 GHz water vapor absorption line with a frequency offset of -7 GHz.

5. Manufacturing Techniques: Laser Machining and the Taper

To manufacture the CSRR design to operate in a WR-2.2 (325–500 GHz) waveguide, laser machining was chosen. The specific laser machining process used has a stated precision of $\pm 10 \mu\text{m}$, with the ability to machine structures as small as $5 \mu\text{m}$ in size. This choice in manufacturing technique allowed the CSRR to be machined as one complete part, in turn mitigating some of the traditional challenges of machining waveguide parts in split block using CNC machining and 3D fabrication processes [9–11]. The filters were machined on a thin metal sheet, aligned with the waveguide alignment pins, and then mounted between two flanges of cascaded waveguide sections for measurement. Reducing the thickness of the CSRR design significantly decreases the insertion loss of the resonator since material losses can be significant at sub-terahertz frequencies. Reducing the thickness of the CSRR design also increases the bandwidth, so a quarter-wave material thickness was chosen as the best compromise for this design to preserve the narrow bandwidth.

Laser Machining Effects

The laser machining process chosen for this work resulted in an unintended taper from the front to the back of the metal sheet, as illustrated in Figure 4, and with photos shown in Figure 5. This is not part of the intended CSRR design, and it is important to evaluate the effect of the machined taper on the CSRR performance.

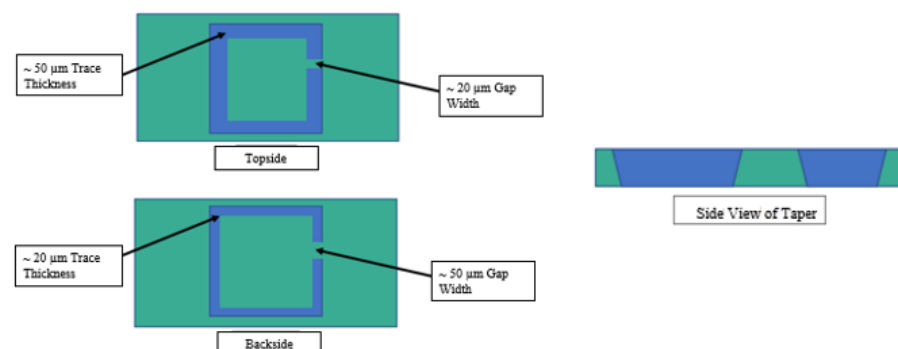


Figure 4. Illustration of a taper resulting from the laser machining process. The backside of the CSRR has the desired trace thickness, while the topside thickness is $30 \mu\text{m}$ greater in thickness than the designed value.

The laser machining process essentially etches the design into a thin metal sheet and is more cost-effective than traditional CNC machining, especially for manufacturing significant quantities. For the CSRR design, the laser machining process produced a $30\text{ }\mu\text{m}$ taper in trace thickness (as defined in Figure 2) from the topside to the backside of the material, as illustrated in Figure 4. This results in the trace thickness on the topside being $30\text{ }\mu\text{m}$ greater than the designed value, as shown in Figure 4. Estimated dimensions for the topside and backside of the fabricated design are also shown in Figure 4.

It is expected that this taper would increase the bandwidth and decrease the insertion loss of the manufactured CSRR designs based on Table 1. The trace thickness and gap length of each of the manufactured CSRRs were measured using optical microscopy. The taper due to laser machining was taken into account as part of the simulations shown in Figure 3. A 3D model of the machined taper was constructed to make the simulation more accurately reflect the manufactured resonator. Simulation results of the resonator with the taper are shown in Figure 6. It is important to note that due to the laser fabrication process, the edge/corners of the design are rounded, so rounded edges are also included in the simulation.

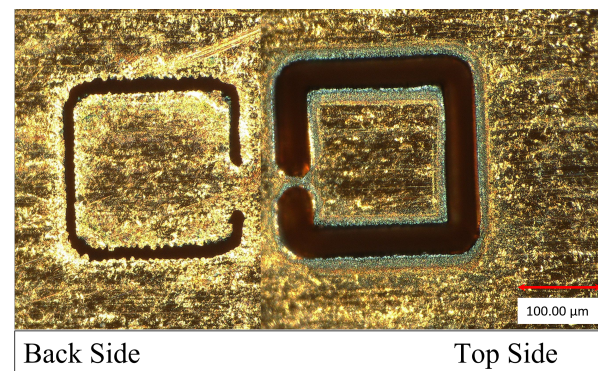


Figure 5. Two images of the CSRR trace under the microscope are shown. The left image shows the backside, and the right image shows the topside. The dimension of $100\text{ }\mu\text{m}$ is provided on the right for scale.

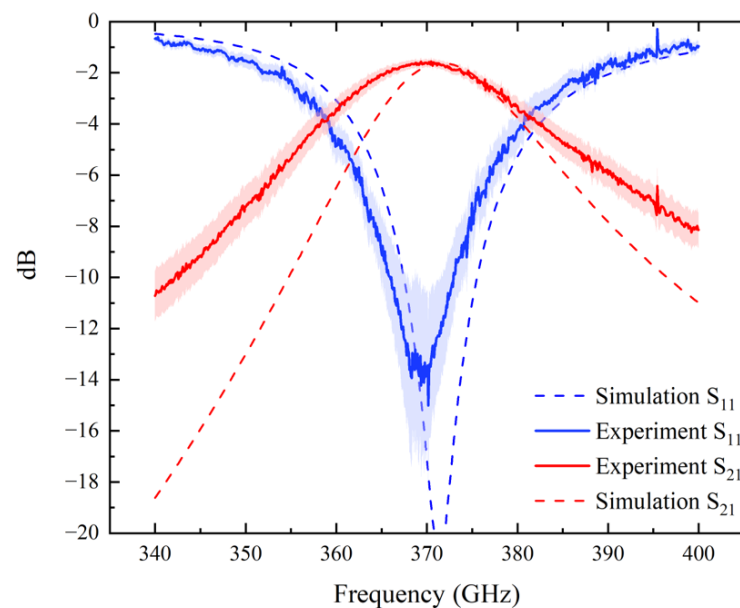


Figure 6. Measured S_{11} and S_{21} for one of the manufactured CSRR resonators, in blue and red solid lines, respectively. The measurement uncertainties of S_{11} and S_{21} are shown by the respective blue and red shaded regions. The simulation responses for S_{11} and S_{21} , including the taper, are shown in the blue and red dashed lines, respectively.

6. Experimental Results

The CSRR design centered at 373 GHz with a bandwidth of 11 GHz was chosen to manufacture on a copper sheet with a 200 μm thickness. Ten units were manufactured using laser machining to determine experimentally the effects of manufacturing variability on resonator performance. The scattering parameters of the 10 manufactured resonators were measured using a VNA with WR-2.2 waveguide extension heads. A VNA calibration was performed using a standard Thru-Reflect-Line (TRL) procedure. The results for one of the 10 CSRR designs are shown in Figure 6, overlaid with the simulated response. The shaded region around the measured insertion loss is the measurement uncertainty, largely due to small errors in alignment of the WR-2.2 (325–500 GHz) waveguide extension heads.

Table 2 provides the center frequency and bandwidth characteristics of the measured spectral responses for the ten resonators. The manufactured designs were shifted lower in frequency by approximately 1.3% compared to the designed value. The insertion loss at the center frequency was measured to be 1.65 ± 0.38 dB. These measured values of CSRR performance agree well with the simulation results, as shown in Figure 6. The mean and standard deviation of the measured bandwidths were $17 \text{ GHz} \pm 4 \text{ GHz}$, compared to the simulated mean value of 11 GHz.

Table 2. Center frequency and bandwidth characteristics of manufactured CSRR design.

Dimension	Center Frequency	Shift in Center Frequency	Bandwidth	Change in Bandwidth
Simulation	373 GHz	N/A	11 GHz	N/A
10 Measured Resonators	368.3 ± 5.6 GHz	1.3% shift downward in frequency	17 ± 4 GHz	1.6% maximum increase in bandwidth

To further evaluate the effects of manufacturing variations, the CSRR traces were measured and photographed under an optical microscope, providing images such as those shown in Figure 5. The existence of the taper is evident, as discussed in Section 5. Measurements of the critical dimensions were taken for each of the ten manufactured CSRRs and are summarized in Table 3. The trace thickness on the topside is 50 μm , while the trace thickness on the backside is 20 μm . The average trace thickness with depth is, therefore, 35 μm , compared to the design trace thickness of 20 μm . This increase in trace thickness explains the downward shift in center frequency for all the CSRR designs, as well as their increased bandwidth, according to the relationships shown in Table 1. For this specific design, the trace thickness substantially affects the bandwidth of the resonator. Partially due to the taper, the CSRR split length (L_s) was 7 ± 1 μm larger than the designed dimension of 50.8 μm , also contributing to the increase in bandwidth, according to Table 1. The third characteristic of interest is the CSRR gap placement on the right side of the trace, referenced to the orientation shown in Figure 2. The CSRR split placement was found to shift clockwise by 7 ± 6 μm from the designed placement, 50.8 μm below the top right corner of the trace. For a clockwise shift of the split placement, the bandwidth is expected to decrease, according to Table 1. In summary, the bandwidth increased from the simulated value due mainly to the taper, including the increased trace thickness (t), increased split length (L_s) and clockwise shift in split placement. The variations in response among the ten manufactured resonators are principally due to manufacturing variations in the laser machining process that caused changes in critical dimensions from the designed values.

Table 3. Critical dimensions for the CSRR design.

Dimension	Original Dimension	Average Manufactured Dimension
Split Length (L_s)	50.8 μm	Increased by 7 ± 1 μm
Trace Thickness (t)	20 μm	Increased by 3 ± 2 μm
Side Length (S)	250 μm	Decreased by 19.1 ± 2.5 μm
Split Placement	50.8 μm from top right corner	Shifted clockwise by 7 ± 6 μm

Comparing the results of this research with previous work, the laser machining used in this work provides dimensional accuracy of critical dimensions of 7 μm or better, while 3D fabrication processes provide 5 μm accuracy, and traditional CNC machining typically provides of the order of 12.5 μm accuracy for high-quality machining. Therefore, the laser machining process offers similar dimensional accuracy to more expensive 3D fabrication processes and is arguably better than traditional CNC machining. In addition, the laser machining process is highly cost-effective, repeatable, and can easily be fabricated on a large scale.

7. Conclusions

This work provides novel contributions on the design and manufacturing considerations of narrow-band waveguide resonators in the upper-millimeter wave or lower-terahertz frequency range using a split-ring resonator design. This design and manufacturing innovation is intended for use at frequencies of 200 GHz and above. The intended application is airborne or space-borne remote sensing of water vapor in the upper troposphere and lower stratosphere using the 380 GHz water vapor line with sensor bandwidths of approximately 3–4%.

A key issue with manufacturing passive waveguide technology above 200 GHz is that the critical design dimensions are of the same order of magnitude as the machining tolerances that are currently available. This design was fabricated using a laser machining process, which provides a measured accuracy of 7 μm or better and the capability to machine objects as small as 5 μm in size. The design achieved acceptable bandwidths for sensing with minor variations in performance due to the laser machining. To the authors' knowledge, this is the only known experimental implementation of a split-ring resonator design in a rectangular waveguide operating above 15 GHz.

This result validated the use of a waveguide-based split-ring resonator for narrow-band sensing of water vapor profiles in the sub-terahertz band, near the 380 GHz absorption line. Although the inductive iris design can achieve narrower bandwidths than the CSRR, our method of fabrication eliminates some of the uncertainty of machining the iris filter in two parts. The result has also validated the use of the laser machining process for thin metal sheets in that the tolerances are similar to other available fabrication methods. Future directions for this work would include the design and fabrication of multi-section CSRR filters across multiple radiometer bands.

Author Contributions: Conceptualization, S.L.W. and S.C.R.; methodology, S.L.W.; validation, S.L.W.; formal analysis, S.L.W.; investigation, S.L.W.; resources, S.C.R.; data curation, S.L.W.; writing—original draft preparation, S.L.W.; writing—review and editing, S.L.W. and S.C.R.; visualization, S.L.W. and S.C.R.; supervision, S.C.R.; project administration, S.L.W. and S.C.R.; funding acquisition, S.C.R. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded in part by the U.S. National Aeronautics and Space Administration, Science Mission Directorate, Earth Science Technology Office as part of the Instrument Incubator Program under grant number NNX14AK70G.

Data Availability Statement: Data is contained within the article.

Acknowledgments: We wish to thank Dazhen Gu from the Shared Spectrum Metrology Group at The National Institute of Standards and Technology (NIST) for his help with providing measurement facilities for this work.

Conflicts of Interest: The authors declare no conflicts of interest.

References

- Jiang, J.H.; Yue, Q.; Su, H.; Reising, S.C.; Kangaslahti, P.P.; Deal, W.R.; Schlecht, E.T.; Wu, L.; Evans, K.F. A Simulation of Ice Cloud Particle Size, Humidity, and Temperature Measurements from the TWICE CubeSat. *Earth Space Sci.* **2017**, *4*, 574–587. [\[CrossRef\]](#) [\[PubMed\]](#)
- Jiang, J.H.; Yue, Q.; Su, H.; Kangaslahti, P.; Lebsock, M.; Reising, S.; Schoeberl, M.; Wu, L.; Herman, R.L. Simulation of Remote Sensing of Clouds and Humidity from Space Using a Combined Platform of Radar and Multifrequency Microwave Radiometers. *Earth Space Sci.* **2019**, *6*, 1234–1243. [\[CrossRef\]](#)
- Klein, M.; Gasiewski, A.J. Nadir sensitivity of passive millimeter and submillimeter wave channels to clear air temperature and water vapor variations. *J. Geophys. Res.* **2000**, *105*, 17481–17511. [\[CrossRef\]](#)
- Kangaslahti, P.; Lim, B.; Gaier, T.; Tanner, A.; Varonen, M.; Samoska, L.; Brown, S.; Lambrigsten, B.; Reising, S.; Tanabe, J.; et al. Low Noise Amplifier Receivers for Millimeter Wave Atmospheric Remote Sensing. In Proceedings of the 2012 IEEE MTT-S International Microwave Symposium Digest, Montreal, QC, Canada, 17–22 June 2012; pp. 1–3.
- Leong, K.M.K.H.; Mei, X.; Yoshida, W.H.; Zamora, A.; Padilla, J.G.; Gorospe, B.S.; Nguyen, K.; Deal, W.R. 850 GHz Receiver and Transmitter Front-Ends Using InP HEMT. *IEEE Trans. Terahertz Sci. Technol.* **2017**, *7*, 466–475. [\[CrossRef\]](#)
- Cooke, C.M.; Leong, C.K.; Zamora, A.; Gorospe, B.S.; Mei, X.B.; Kangaslahti, P.; Schlecht, E.; Ogut, M.; Goncharenko, Y.; Reising, S.C.; et al. A 670 GHz Integrated InP HEMT Direct-Detection Receiver for the Tropospheric Water and Cloud Ice (TWICE) Instrument. *IEEE Trans. Terahertz Sci. Technol.* **2021**, *11*, 566–576. [\[CrossRef\]](#)
- Bosch-Lluis, X.; Kangaslahti, P.; Ramos, I.; Ogut, M.; Tanner, A.; Cooperrider, J.; Munoz-Martin, J.F.; Yue, Q.; Deal, W.R.; Cooke, C.M. Smart Ice Cloud Sensing (SMICES): An Overview of its Submillimeter Wave Radiometer. In Proceedings of the IGARSS 2022—2022 IEEE International Geoscience and Remote Sensing Symposium, Kuala Lumpur, Malaysia, 17–22 July 2022; pp. 4296–4299. [\[CrossRef\]](#)
- Prigent, C.; Pardo, J.R.; Rossow, W.B. Comparisons of the Millimeter and Submillimeter Bands for Atmospheric Temperature and Water Vapor Soundings for Clear and Cloudy Skies. *J. Appl. Meteorol. Climatol.* **2006**, *45*, 1622–1633. [\[CrossRef\]](#)
- Zhuang, J.-X.; Hong, W.; Hao, Z.-C. Design and Analysis of a Terahertz Bandpass Filter. In Proceedings of the 2015 IEEE International Wireless Symposium (IWS 2015), Shenzhen, China, 30 March–1 April 2015.
- Cooke, C.M.; Arroyo, J.; Zhang, K.; Escorcia, A.; Nguyen, K.; Deal, W.R. Narrow-band Band-pass Filters for Terahertz Applications. In Proceedings of the 2021 IEEE MTT-S International Microwave Symposium (IMS), Atlanta, GA, USA, 7–25 June 2021; pp. 196–199. [\[CrossRef\]](#)
- Koller, D.; Bryerton, E.W.; Hesler, J.L. WM380 (675–700 GHz) Bandpass Filters in Milled, Split-Block Construction. *IEEE Trans. Terahertz Sci. Technol.* **2018**, *8*, 630–637. [\[CrossRef\]](#)
- Zhao, X.; Shan, G.; Du, Y.; Bao, J.; Zhu, H.; Zheng, Y.; Shek, C.; Cheng, Y. G-Band Rectangular Waveguide Filter Fabricated Using Deep Reactive Ion Etching and Bonding Processes. *IET Micro Nano Lett.* **2012**, *7*, 1237–1240. [\[CrossRef\]](#)
- Ding, J.; Shi, S.; Zhou, K.; Zhao, Y.; Liu, D.; Wu, W. WR-3 Band Quasi-Elliptical Waveguide Filters Using Higher Order Mode Resonances. *IEEE Trans. Terahertz Sci. Technol.* **2017**, *7*, 302–309. [\[CrossRef\]](#)
- Feng, Y.; Zhang, B.; Liu, Y.; Liu, J.; Niu, Z.; Yang, K.; Fan, Y.; Chen, X. WR-2.8 Band Pseudoelliptic Waveguide Filter Based on Singlet and Extracted Pole Resonator. *IEEE Access* **2019**, *7*, 54705–54711. [\[CrossRef\]](#)
- Wang, J.; Zhao, Y.; Ding, J. 400 GHz Easy-Packaging Waveguide Filters Based on Mixed-Mode and Off-Axis Couplings. *IEEE Access* **2021**, *9*, 76642–76648. [\[CrossRef\]](#)
- Joannopoulos, J.D.; Johnson, S.G.; Winn, J.N.; Meade, R.D. *Photonic Crystals: Molding the Flow of Light*; Princeton University Press: Princeton, NJ, USA, 1995.
- Ali, A.; Mitra, A.; Aïssa, B. Metamaterials and metasurfaces: A review from the perspectives of materials, mechanisms and advanced Metadevices. *Nanomaterials* **2022**, *12*, 1027. [\[CrossRef\]](#) [\[PubMed\]](#)
- Li, S.; Liu, H.; Sun, Q.; Huang, N. A Tunable Terahertz Photonic Crystal Narrow-Band Filter. *IEEE Photonics Technol. Lett.* **2015**, *27*, 752–754. [\[CrossRef\]](#)
- Wang, Y.; Yang, B.; Tian, Y.; Donnan, R.S.; Lancaster, M.J. Micromachined Thick Mesh Filters for Millimeter-Wave and Terahertz Applications. *IEEE Trans. Terahertz Sci. Technol.* **2014**, *4*, 247–253. [\[CrossRef\]](#)
- Arriola, W.A.; Kim, Y.-S.; Lee, J.-W.; Kim, I.S. Bandwidth of Complementary Split Ring Resonator for Rectangular Waveguide BPFs. *IEEE Microw. Wirel. Components Lett.* **2016**, *26*, 669–671. [\[CrossRef\]](#)
- Wang, H.; Huang, Y.; Ma, S.; Ni, C.; Huang, Z.; Wu, X. High transmittance band-pass plasmonic filter using metal-insulator-metal waveguide with double split circular ring resonator. In Proceedings of the 2022 International Conference on Microwave and Millimeter Wave Technology (ICMMT), Harbin, China, 12–15 August 2022. [\[CrossRef\]](#)
- Chowdhury, D.R.; Singh, R.; O'Hara, J.F.; Chen, H.; Taylor, A.J.; Azad, A.K. Photo-doped silicon in split ring resonator gap towards dynamically reconfigurable terahertz metamaterial. In Proceedings of the Conference on Lasers and Electro-Optics 2012, San Jose, CA, USA, 6–11 May 2012. [\[CrossRef\]](#)

23. Feng, A.; Yu, Z.; Sun, X. Giant enhancement of nonlinear optical processes with split-ring resonators for THz applications. *IEEE Photonics Technol. Lett.* **2019**, *31*, 1681–1684. [[CrossRef](#)]
24. Kaur, S.; Karmakar, S.; Varshney, R.K.; Chowdhury, D.R. Effect of split ring resonator on transmission characteristics of Dipole metacavities. In Proceedings of the CLEO 2023, San Jose, CA, USA, 7–12 May 2023. [[CrossRef](#)]

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.