Waveguide and FSS Inspired Waveguides Array: A Comprehensive Review

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ABSTRACT

This paper presents a detailed survey of waveguides and the most recent research efforts on SRR inspired waveguides. These are basically classified into various categories, such as arrays based on slot waveguides, open-ended waveguides, split ring resonators (SRR) based waveguides, and planar structure-embedded waveguides. Some practical difficulties or limitations for the development of these arrays have been illustrated, and their possible solutions are also suggested. A detailed review of different types of waveguide arrays has been included for researchers understanding.

Keywords: Waveguides, Slot Antenna, Split Ring Resonators, SRR Inspired Antennas

1. INTRODUCTION

With the rapid development of RF technology, demands for advanced multiband antennas have risen very rapidly over the past few decades. Such antennas receive signals for selected bands of frequencies and restrict others, thus reducing the probability of out-of-band interference. Though at present miniaturized, low-profile planar antennas are the first choice of RF engineers, waveguide-based antennas have not lost their importance because of their unique advantages like high power handling capability, ruggedness, low dielectric loss, etc. Planar antennas are not very suitable for high-power applications like radars, ground station systems for satellite communication, etc. as they have low power handling capability.

The waveguide slot antenna was used before World War II. The early works on the slotted waveguide were done by Watson, Stevenson, and Booker. The theoretical analysis was done by Stevenson [1], while the experimental work was done by Watson [2]. Booker [3] analyzed the equivalence principle of slot and dipole based on the Babinet principle. Ajioka et al. [4] proposed slots in the narrow wall of a waveguide that can support both the odd and even modes. Hsu and Chen [5] investigated the resonant length and admittance properties of a titled slot on the narrow wall of a waveguide. The frequency restriction on the broad-band performance of a slot array was presented by Hamadallah [6] in 1989. The author suggested two methods to predict the bandwidth and broadband performance of waveguide slot arrays. Compound slots on the broad wall of a rectangular waveguide were briefly reported by Rengarajan [7].

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2. WORK ON WAVEGUIDE SLOT ANTENNA

The waveguide slot antenna has been used since 1960. Slot waveguide arrays find applications in radar and satellite communication due to their various advantages like moderate gain, high power handling capability, low loss, and simple fabrication procedures. A survey outline on slotted waveguide arrays has been provided below.

In 2001, Park et al. [24] analyzed a radiating slot in the broad wall of a waveguide using finite element methods. The proposed method has been useful for the characterization of radiating slots. They also showed that the results obtained from this method have good agreement as compared to the conventional methods. The mutual and self-admittance of a transverse slot in a slotted waveguide cylindrical structure has been analyzed by Wettergren [8]. The analysis is based on the expansion of the basis function for each radiating slot aperture. It revealed that the presented analysis is useful to determine the value of aperture admittance. A transverse slotted waveguide antenna filled with H-plane dielectric slabs was designed by Shan and Shen in 2004 [9]. The analysis revealed that the dimensions of the waveguide and guided wavelength can be reduced by the partial insertion of a dielectric slab. It was also shown that partially filled slab structures have a wider bandwidth compared to waveguides fully filled with dielectric slabs. Farrall et al. [10] presented a slotted waveguide array integrated with planar structures in the same year. The size of the structure was more compact as compared to the other planar slotted waveguide array. A full wave analysis of a resonant slot in the broad wall of a rectangular waveguide was reported by Ren et al. [11] using FDTD. The analysis was done for four different types of slots, including longitudinal shunt slots, transverse or longitudinal coupling slots, compound slots, and coupled center inclined slots. Slot admittances for various offsets, resonant lengths, and tilt angles were found. The slot characteristics are useful for designing the high-performance slotted waveguide array. The complete theory of TE00 mode for a rectangular waveguide was analyzed by Eshrah et al. [12] in 2004.

In 2005, Oh, Wang, and Choi [13] reported a single-layer slotted waveguide antenna with diaphragms. A 16×16 slotted waveguide antenna with inductive diaphragms was presented in this paper. They achieved 31.2 dBi gain and were below the -18 dB side lobe level.

A dual-polarized waveguide slot array integrated with interdigital structures was proposed by Park et al. [14]. The integration of an electromagnetic bad gap structure (EBG) in the waveguide slotted antenna was proposed by Li et al. in [15] 2006. A 5 × 5 element slotted waveguide integrated with mushroom-type EBG was analyzed. The analysis showed that the surface waves were highly suppressed in the proposed structure as compared to the standard slotted waveguide. As a result, the back radiation decreased and the gain improved. In 2006, Park et al. [16] proposed a single-layer slotted waveguide antenna with a center feed to suppress the frequency-dependent beams and improve the bandwidth by using a genetic algorithm. It was shown that the side lobe has been suppressed as compared to conventional slotted waveguide structures. In 2006, Casula, Mozzarella, and Montisci [17] extended the work on partially filled slotted waveguides with dielectric slabs. The work was devoted to overcoming the drawbacks of a previously designed slot array.

A broadband longitudinal slot waveguide array having compact transverse dimensions was reported by Wang et al. [18]. The proposed array is separated by two sub-arrays, which are fed by a convex waveguide power divider to enhance the bandwidth. A tilted edge slot in the rectangular waveguide was analyzed by Young et al. [19] in 2007. The author suggested that this approach has vital advantages in two-dimensional models like baffles. High-impedance surfaces employed in the ground plane of slotted waveguides to improve the radiation characteristics were reported by Gao [20]. The analysis suggested that the insertion of high-impedance EBG structures in the ground plane of the slot waveguide reduces the back lobe level and increases the gain of the array. They also achieved a reduction in mutual coupling by 8–10 dB. Kim and Eom [21] analyzed the mode matching models for the longitudinal slot waveguide array. The method estimated the exact radiation pattern for a longitudinal slot waveguide array without much mathematical calculation. In the same year, Ebadi et al. [22] presented an annular waveguide slotted array. An equivalent circuit model was suggested for this structure based on its similarity to the slotted waveguide. In 2010, Kim and Lee [23] designed a compact resonant slot waveguide antenna partially filled with H-plane waveguide. They showed that the cross section of the waveguide can be reduced by up to 75% while maintaining the same characteristics as a conventional slotted waveguide. Another slot array design for low side lobe levels was proposed by Rengarajan et al. [24]. A wideband eight-element slotted waveguide array for synthetic aperture radar applications was presented by Zhao et al. [25]. It revealed that elliptical slots on the conventional waveguide can enhance the bandwidth of the waveguide slot array. In 2011, Tan et al. [26] proposed a highly efficient slotted waveguide antenna for a small radar cross section (RCS). They combine both artificial magnetic and perfect electric conductors to achieve a low value of RCS. Besides the radiation characteristics, they were also improved. Lokke and Ostergaard [27] proposed an accurate and efficient network model for non-resonant inclined slots in the narrow wall of a waveguide. The model predicts the radiation patterns, power dissipated into the load, return loss, slot conductance, tilt angle, waveguide loss, etc. Liu et al. [28] analyzed the mode and dispersion relations for a transverse slot in the rectangular waveguide. They also analyzed the difference between dielectric and air-filled waveguides with transverse slots. A higher-order method of moment-based analysis for edge waveguide slot arrays was presented by Lai et al. [29] in the same year. In 2012, Nicholson et al. [30] reported a stiffened waveguide slot antenna structure. It was observed that for sub-resonant slots with wire element gain, the gain is the same as for conventional resonant slots. An accurate characterization of a longitudinal slot having a cavity was presented by Montisci et al. [31] by the method of moment. It revealed that the proposed technique is faster than Ansys HFSS. A planar antenna fed by a waveguide shunt slot was reported by Sood et al. [32]. In 2014, Daliri et al. [33] presented a split ring slot milled on the broad wall of a rectangular waveguide. The major advantage of this structure is the size of slots is smaller than a conventional slot. It was shown that designed slot (0.186 part of wavelength) radiates linear polarized wave similar to conventional half wavelength slots. Resonant and admittance characteristics of a longitudinal slot covered with dielectric material were presented by Amini and Forooraghi [34]. Ebadi and Semnani [35] designed a EBG structure in the slotted waveguide for reduction of mutual coupling. It has been shown that for a non-similar waveguides mutual coupling between the slots is significantly reduced. Fabricated view of the EBG-loaded waveguide slot array fig. 1. Next year, in 2016, Wang et al. [36] proposed a square cavity-backed slot waveguide to attain wide-band circular polarization. The cavity-backed slotted array was designed to achieve directional radiation patterns. A circularly polarized slotted radiator with improved axial ratio (AR) bandwidth has been reported by Rocher et al. [37]. The analysis revealed that the axial ratio bandwidth is improved due to the use of parasitic dipoles. Two pairs of corner or edge slots milled on cavity surfaces that have been located just above the cross slot were proposed by Wu et al. [38] to achieve circular polarization. In a narrow wall waveguide, beam steering using a rotating dielectric slab was proposed by Ghasemi et al. [39]. In the next year, a continuous beam steering slotted antenna was presented by Ghasemi and Laurin [40] in 2019. Two dielectric slabs inside the slotted waveguides had been in charge of beam steering.

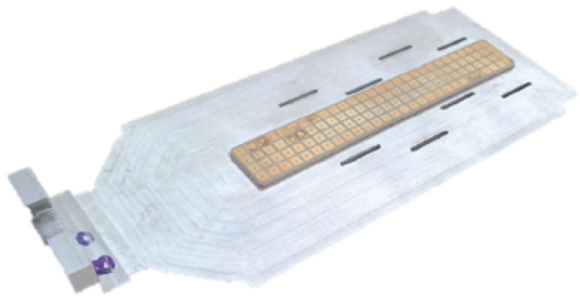


Fig. 1: Fabricated view of EBG Loaded waveguide slot array.

Higher-order mode coupling among the neighboring slot and inclined slot has been designed by Coetzee et al. [41]. Recently, in 2020, a T-shaped high-gain circularly polarized slotted waveguide antenna was designed by Dimitrov et al. [42]. Two T-slots have been designed among the slots.

3. OPEN ENDED WAVEGUIDES ARRAY

Open-ended waveguides (OEW) find applications in radar and satellite communication due to their various advantages, like moderate gain, high power handling capability, low loss, and a simple fabrication procedure. A survey outline on OEW has been provided below.

In 1984, Yaghjian [43] derived the approximate formula for the far-field parameters and gain of an open-ended waveguide. This expression is helpful to predict the gain value with great accuracy as compared to existing Stratton-Chu methods, which give the gain value lower than 2-3 dB. Based on theoretical and experimental analysis, the comparison of the gain of an OEW and a horn antenna was presented by Kanda et al. [44] in 1987. The presented antenna gain was calculated using the three-antenna method. Altintas et al. [45] studied EM coupling and radiation behavior in an OEW. Radiation behavior and full wave analysis of an OEW antenna were reported by Baudrand et al. [46] in the same year. The transverse operator method was used for this purpose. EM scattering by an open-ended waveguide cavity was analyzed by Pathak et al. [47] in 1989 by ray, modal, and beam approaches. A comparison for the near-field calculation of an open-ended waveguide based on theoretical and experimental observation was done by Wu and Kanda [48]. They proposed two different methods for near-field calculation: one is the plane wave equation, in which the electric field has been expressed in terms of gain, and the other is the far-field to near-field transformation.

In 1992, Sibbald et al. [49] presented an admittance model for an open-ended waveguide antenna that radiates homogenously. The suggested model is basically based on the mathematical and physical properties of single-port driving point admittance. The line integration formulation for an open-ended waveguide was represented by Maci et al. [50] in 1997. The model was formulated taking advantage of the equivalence between the radiation of modal current and aperture along semi-infinite waveguide walls. Mioc et al. [51] proposed a double-line integration formulation to investigate the mutual coupling between the open-ended waveguide antennas having arbitrary cross-sections. In 1998, Kashyap, Louie, and Paknys [52] investigated the EM scattering from the open-ended waveguide. The authors used the methods of moment and model aperture integration for this analysis. A comparison of open-ended waveguide antenna radiation patterns based on exact and heuristic models was presented by Perov et al. [53] in 2004. The proposed method provides accurate radiation patterns for dominant and higher-order modes. Wang and Asfar [54] reported a calibration technique for the measurement of the reflection coefficient of an open-ended waveguide. The presented technique is very useful for the measurement of permeability and permittivity by using an open-ended waveguide.

In 2008, a triangular open-ended waveguide array was designed by Simeoni et al. [55]. The authors suggested a possible feeding mechanism and array arrangement for phase array systems. Next year, in 2009, Hebib et al. [56] presented a pyramidal OEW radiator, which is useful for satellite applications. Enkhbayar, Bang, Cha, and Ahn [57] demonstrated a new formulation for the gain calculation of an open-ended waveguide antenna. The presented formula included the possible effects of waveguide wall thickness. The radiation behavior of an open-ended waveguide array was investigated by Coburn et al. [58] by analytical and full-wave simulation in 2010. In 2011, Ludlow and Fusco [59] designed a polarization-aggressive evanescent open-ended waveguide array. It was shown that depending on the excitation, both circular and linear polarization can be achieved. The presented array is also capable of producing LHCP or RHCP patterns.

In 2013, Ludlow et al. [60] reported an evanescent mode-supported waveguide array with a small aperture by applying the band-pass filter technique. The presented design allows the matching of the aperture admittance of an open-ended waveguide antenna with a real impedance generator. It revealed that the designed array is suitable for phased array applications. A wide-band dual-polarized waveguide antenna was proposed by Maruyama et al. [61] in 2014. They used stack-fed circuits on the different substrates to achieve dual polarization. In 2017, Escuderos et al. [62] presented a multimode equivalent network model for a finite array of open-ended waveguides. The major advantage of this network is that it is fully compatible with other waveguide junctions like complex power dividers, filters, etc. that have been connected to the radiating aperture of an open-ended waveguide. In the next year, dual-band collinear-fed circularly polarized OEW was reported by Honari et al. [63]. The presented techniques are suitable for high-power applications, and they can be used as feeder elements for various arrays such as metasurface and surface wave antennas. In 2020, an element-based circularly polarized OEW antenna was presented by Mao et al. [64].

4. SRR LOADED WAVEGUIDES

In 1968, Veselago [65] theoretically analyzed EM propagation through a left-handed medium. However, no left-handed media was known to exist at that time. In 2003, F. Medina et al. [66] Left-handed characteristics can be achieved by using periodic split-ring resonators (SRR) and thin wire structures. After that, the SRR structure created attention among the researchers. In 2005, the equivalent lumped circuit parameters of SRR and CSRR were analyzed by Baena et al. [67]. They investigated the electromagnetic behavior of these elements. The equivalent model was shunt capacitance and mutual inductance. Harbar [68] proposed a waveguide filled with anisotropic materials of negative permeability in the same year. The analysis showed that these types of waveguides support backward waves below the cutoff frequency. A waveguide array antenna with reduced aperture was reported by Park et al. [69–70] by using SRR. The author showed that a 70% aperture reduction is possible by embedding SRR structures in the feed waveguide. Next year, Ju et al. [71] showed some improvement in the aperture reduction. They suggested that the aperture can be reduced up to 88%. Another approach to implementing multiple passband band characteristics in a waveguide is to keep a filtering structure at the input port of the array. Fallahazadeh et al. have used two square-shaped split-ring resonators in the same transverse plane of a waveguide to design a dual-band waveguide band-stop filter [72]. In the presented model, the resonators have been inserted far apart. So that the coupling introduced between their resonators becomes poor and the notch bands have been controlled independently by adjusting resonator lengths.

A multi-band SRR based waveguide was presented in 2009 [73]. It revealed that the passbands and stopbands can be tuned by using different sizes of resonators as well as different substrates. The fabricated structure is depicted in Fig. 2. The requirement of adjustment of the resonator at long distances on the same planes limited the maximum number of resonators that could be used (because of the restricted cross-sectional area inside the waveguide), so it also restricted the number of stop-bands. In addition, they designed two split-ring resonators with different dimensions to design the filter, which also restricted the tuning of bandwidth. The problem of the above method has been solved by Kehn et al. [74], who inserted a planar array of four different sizes of resonators between the walls of the waveguide to attain four stop-bands. Moreover, the suggested approach is not efficient. So that the filter size is too big and bulky. The fabricated structure is shown in Fig. 3.

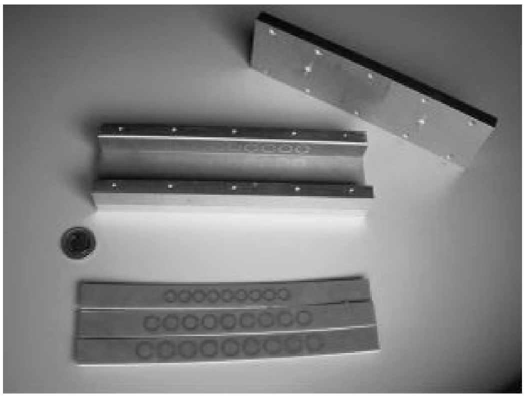


***Fig. 2**: SRR Loaded multiband waveguides.*

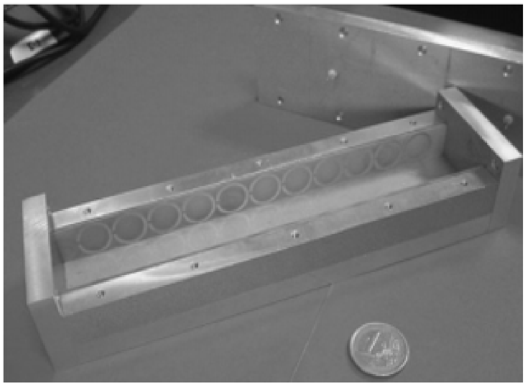


***Fig. 3**: Unequal SRR loaded waveguide.*

***Fig. 4**: Fabricated horn filtennas.*

Evanescent mode waveguide arrays by using band pass filter techniques were presented by Ludlow et al. [75] in 2013. In 2015, horn filtenna with wide stop band behavior was reported by Barbuto et al. [76] by using SRR. The dualband characteristic was obtained by using resonators of different sizes at a certain distance from the throat of the horn. The fabricated horn filter embedded with notch filters has been shown in Fig. 4.

***Table 1**: Qualitative comparison of the different FSS based waveguide based Array.*

References	Return Loss Bandwidth	Gain at Matching Frequency (dB)	FBRR (dB)	Polarization	Technology
[35]	8.6-9.5 GHz	15.2	Not Reported	Linear	Mutual Coupling reduction by EBG loaded slotted waveguide
[77]	8.23-9.23, 9.41-11.01 GHz	8-11	>20	Linear	SRR embedded in transverse plane of slot waveguide
[78]	8.38-8.6 GHz, 9.17-9.43 GHz, 10.63-11.34 GHz	10.45, 10.15, 6.84	20-32	Linear	SRR embedded in transverse plane of slot waveguide
[79]	8.55-8.85 GHz, 9.2-9.4 GHz, and 10.3-10.94 GHz.	6.5-8.5	22-27	Linear	Mutual coupling reduction and Performance improvement in Open ended waveguide by SRR
[80]	8.41-8.88 GHz and 9.31-10.43 GHz	7-8	>20	Linear and Circular	Metasurface Loaded slot waveguide
[81]	8.48-8.69 GHz and 11.4-12.10 GHz	6-8	20-25	Circular	Superstrate and CSRR loaded open ended waveguide to achieve the circular polarization
[82]	9.15-9.47 GHz	8.2-9.3	Not Reported	Circular	Metasurface inspired open end waveguide to obtain RHCP
[83]	15.4-16.2 GHz	5-10	Not Reported	Circular	Metasurface inspired waveguide for beam scanning

***Fig. 5**: Fabricated view of single SRR loaded two element Antenna.*

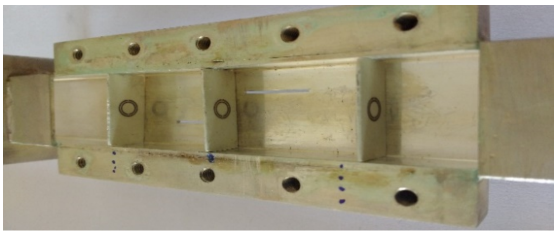


***Fig. 6**: Fabricated multiband slot array radiator.*

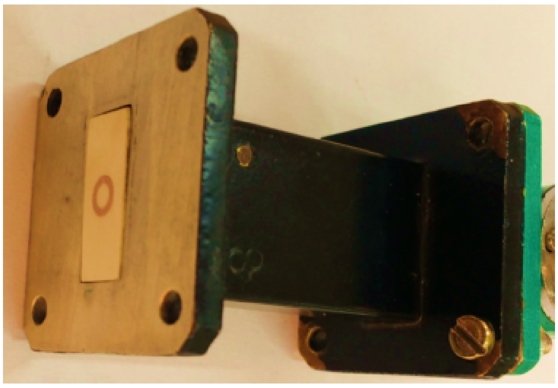


***Fig. 7**: 3D view of the triple band Fabricated Antenna.*

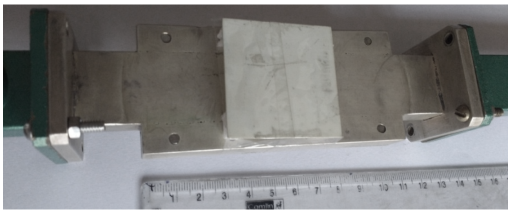
5. PERFORMANCE ENHANCEMENT AND IMPROVED RADIATION CHARACTERISTICS OF FSS INSPIRED WAVEGUIDES

Moreover, the above-mentioned [71–76] techniques have major drawbacks. Implementation of different SRR structures or SRRs of unequal dimensions has fabrication complexity. In addition to manual insertion of the SRRs structures in the H- plane of the waveguide brings additional dielectric losses due to large substrate area has been used. It is very difficult to accurately place a long substrate in the H-plane of the waveguides. One approach to illustrate the multiband characteristics of the waveguide is the insertion of resonators in the transverse plane of the waveguide. Due to these, waveguide-fed slots have found an important place in array antennas as radiating or coupling elements. Waveguide-fed aperture arrays are often used for designing multiband antennas. In the ground plane of the aperture, frequency-selective surfaces or resonators have been loaded to attain multi-band behavior. In addition, with a suitable design and a good front-to-back radiation ratio, a radiation pattern with high gain and very low cross-polarization can be achieved using this technique. Fig. 5 shows the multiband, two-element slotted antenna [77]. To form the antenna, three single split-ring resonators have been placed inside the 2-element slot waveguide. The presented resonators were manufactured on Rogers RO 4350 with a permittivity of 3.3. The equivalent circuit and full wave simulation have been carried out by the authors. The proposed antenna has good matching at 8.88 and 10.30 GHz with respective return losses of 20.08 and 25.06 dB. The designed antenna has a higher gain and front-to-back radiation ratio (FBRR) as compared to conventional slotted waveguides.

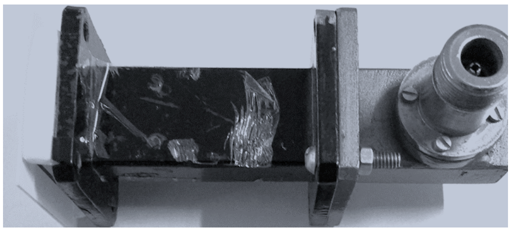
But the antenna has dual-band behavior. So to improve the radiation characteristics of slotted waveguides, another approach to achieve the tri-band nature is to place the double SRRs in a uniformly placed waveguide. The presented geometry [78] of the array is shown in Fig. 6. The proposed SRRs are fabricated on Rogers RO4350 materials for an operating frequency of 10 GHz. Due to the mutual coupling of resonators, the fabricated antenna has a triple-band nature. The proposed antenna has good matching at 8.6, 9.4, and 10.8 GHz with respective 10 dB return loss bandwidths of 8.38-8.69 GHz, 9.17-9.43 GHz, and 10.63-11.34 GHz. The scattering parameters of a multiband radiator have been shown in Fig. 6. The proposed antenna had a more directive nature as compared to the previous one.

But the problems with the above antennas are that the fabrication costs of cut waveguides are very high and.The manual placement of the SRR cells inside the conventionally cut slotted array introduced fabrication errors. Which means the fabricated antennas have little radiation efficiency and acceptably low power. Another disadvantage is that it is a two-port network, so maintaining 10 dB insertion loss has been a very challenging task. Due to fabrication errors it had been less than 10 dB. So radiated power has also been lower at operating frequencies. Chandra et al. [79] proposed the same radiation behavior in open-end waveguides. The 3-D view of an open-ended radiator has been shown in Fig. 7. The SRRS are kept in the open-end waveguides. Initially, SRRs were designed at the 10 GHz operating frequency. The proposed array operated at frequencies of 8.8, 9.32, and 10.3 GHz. The accepted power of the open-end waveguide is more than 95%. Another important parameter of the antenna had been determined by the authors. The coupling mechanism had been investigated by the authors for the first time. The proposed array also has a filtering nature.

The presented antenna in [80] is linearly polarized. Moreover, it is not very suitable for satellite applications. With increasing demand and rapid developments in communication technologies, these systems are now multi-functional. To fulfill the above requirements, ever-more rigorous specifications in RF antenna technology are required, i.e., circular polarization, frequency, polarization diversity, etc. Antennas that employ frequency diversity techniques require an antenna that can operate at distinct frequencies, whereas polarization diversity techniques require an array that operates at different polarizations at the same time. To overcome these problems, a multiband circularly reconfigurable polarized antenna



(a)



(b)

***Fig. 8**: 3D view of (a) dual band dual polarized antenna (b) circularly polarized dual band antenna.*

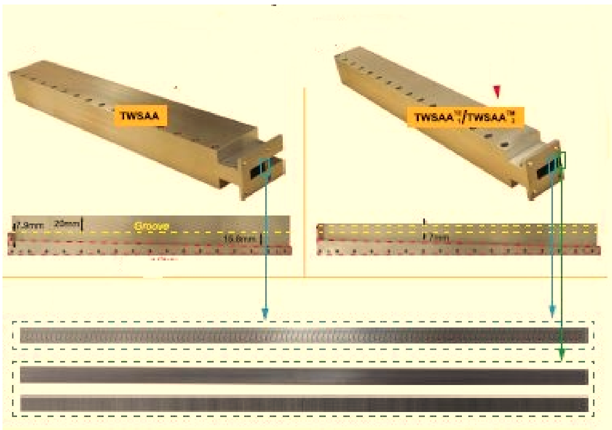


***Fig. 9**: Fabricated antenna.*

was designed [81–82]. The proposed array has dual-band dual-polarized and dual-band circularly polarized characteristics. The proposed array is shown in Fig. 8(a). The assembled view of the fabricated antenna is shown in Fig. 8 (b). The presented circularly polarized array has better radiation behavior as compared to the previously reported array. One major advantage of this array is its polarization reconfiguration characteristics. Recently, Yang et al. [83] proposed a metasurface-based waveguide slotted antenna for wide-angular scanning. The performance has been analyzed by a linearly tapered rectangular waveguide slotted radiator using a spatially angular filtering metasurface. The fabricated structure is shown in Fig. 9. Rectangular waveguides slotted for satellite communication applications were reported by Yuan et al. [84] in 2019. They used metallic sheets to create passbands and stopbands. A qualitative comparison of the different FSS based waveguide based arrays has been reported in Table 1.

6. CONCLUSION

In this communication, the state of the art of waveguide and waveguide-inspired antenna technology is discussed, as are the recent advances in the field of waveguide and antennas implemented by filtering structures. This paper briefly illustrates the new development of SRR loaded waveguide arrays. Moreover, for the design of a circularly polarized array, some novel approaches have been presented. However, the design of the array is also addressed in this paper, which shows polarization reconfiguration. But there is one major drawback to the antenna: we manually achieve the polarization reconfiguration. There is great hope that they may be able to provide electrical reconfiguration, beam steering, and better performance for wireless communication systems. We are looking forward to observing more engineering applications of these arrays in the near future.

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