On the Behavior of Self-Triplexing SIW Cavity Backed Antenna With Non-Linear Replicated Hybrid Slot for C and X-Band Applications

AMIT KUMAR1, MUNISH KUMAR2, (Graduate Student Member, IEEE), AND AMIT KUMAR SINGH1

1Department of Electronics Engineering, IIT BHU, Varanasi, Uttar Pradesh 221005, India
2University School of Information, Communication and Technology, Guru Gobind Singh Indraprastha University (GGSIPU), Dwarka, New Delhi 110078, India

Corresponding author: Amit Kumar (amitk.rs.ece17@iitbhu.ac.in)

ABSTRACT In this paper, a substrate integrated waveguide (SIW) based self-triplexing antenna (STA) with non-linear replicated hybrid slot (NLR-HS) is presented. To the author’s best knowledge, the concept of NLR is the first of its kind in the literature used for obtaining self-triplexed operation. Initially, the SIW cavity is loaded by a hexagonal slot merged with two rectangular transverse slots that together produce two distinct resonances around 5.23 and 7.50 GHz. The variation in resonant frequencies of both lower and upper frequency bands can be modelled by applying NLR on the hexagonal slot. To achieve the self-triplexing operation, a coaxial probe-fed parasitic hexagonal patch is placed concentrically inside the hexagonal slot. The third resonance is centered around 10.82 GHz and can be modelled with the help of the gap between the hexagonal slot and parasitic patch. To validate the proposed idea, the design is fabricated and experimentally tested. Moreover, the antenna shows a front-to-back ratio (FTBR) better than 25 dB, average isolation of 43 dB and measured gain (efficiency) values of 7.33 (97.39%), 6.66 (95.82%), and 6.28 (97.83%) dBi at three resonances. Good agreement between the simulated and measured results makes the proposed STA a good candidate for practical applications.

INDEX TERMS 5G, cavity-backed antenna, non-linear replication (NLR), self-triplexing, sub-6 GHz, substrate integrated waveguide (SIW).

I. INTRODUCTION

The rapid growth in wireless communication systems has increased the demand of multiband/multi-standard antennas for various operations [1]. Various wireless applications such as mobile handheld devices [2] and RF front-end systems [3] require multiple transceivers to operate in different frequency bands. Hence, self-multiplexed antennas receive huge attention due to their simple and compact size with no requirement of decoupling network [4], better isolation between the excitation ports and ease of integration with the RF front-end components [5], [6].

Different self-diplexing/triplexing antennas (SDA/STA) have already been designed in the previous literature using techniques such as defected ground structures (DGS) [7], metamaterial [8], multilayered configuration [9], split ring resonators (SRRs) [10] and spiral defected resonators [11].

However, tuning of resonant frequency in these multiplexers is hard to achieve. Also, their integration with the planar circuits (especially multilayered multiplexers) is highly difficult and challenging task [12]. Also, when a single patch is excited using orthogonally placed feed lines, the isolation between the ports is hard to achieve (especially when \( \frac{f_L}{f_H} \) approaches 2) [13]. One solution to these problems is implementation using substrate integrated waveguide (SIW) technique that exhibits attracting features such as low back-lobe radiation, improved isolation between/among the excitation ports and easy integration with planar circuits [14]–[16]. Most recently, SIW based STAs with intrinsically isolated input ports and independently tuned frequency bands are discussed in [17], [18]. In [17], a SIW based STA having two bow-tie shaped slots are etched on a SIW cavity is proposed. The position of the slots is varied to obtain the three distinct independently tuned frequency bands centered around 7.89/9.44/9.87 GHz. Another SIW based STA designed for 4.18/5.2/5.8 GHz frequency bands is discussed.
in [19] where two different SIW cavities are formed, i.e., outer cavity with two transverse slots for 4.18/5.2 GHz and inner cavity with annular slot for 5.8 GHz frequency band. A similar concept with modified outer cavity is presented in [20]. The outer and inner cavities of the proposed STA supports 4.8/5.4 GHz and 3.5 GHz frequency bands, proving its suitability for 3.5/4.8/5.4 GHz WLAN, WiMAX and 5G wireless standards. The STA presented in [21] uses the innovative concept of hybrid SIW cavity resonator (combination of half-mode circular and rectangular SIW cavities) for the generation of 5.57/7.17/7.65 GHz frequency bands. The excitation ports are separated with the help of T-shaped slots. Another STA supporting 5.6/6.64/6.95 GHz with T-shaped slot etched in the metallic ground plane is discussed in [22]. Here, three shorted-vias are introduced for good isolation of better than 25 dB among the excitation ports. Reference [23] also uses the idea of half-mode rectangular SIW cavity for 4.95/5.3/5.9 GHz WLAN wireless application. The proposed STA consists of an inverted V-shaped slot etched on the SIW cavity which divides it into two sub-cavities, one eight-mode while other one quarter-mode. Another STA with improved port isolation, i.e., more than 28.4 dB is proposed in [24]. The proposed STA comprises of modified I-shape slot intently designed for 4.14/6.1/8.32 GHz frequency bands. In [18], the reported work shows a dumbbell shaped slot placed on the SIW cavity to radiate at 6.76/8.62/13.33 GHz, thus supporting C-, X- and K3 frequency bands simultaneously. Though the aforementioned STAs achieve good performance characteristics such as high isolation among the excitation ports and gain/efficiency levels, still more compact and independently tuned STAs with lesser number of tuning parameters are needed to be explored.

Here, a compact SIW based STA with two orthogonally placed microstrip feed lines and one coaxial probe is presented. The proposed design consists of a single large SIW cavity designed over a single substrate layer with a hybrid slot which is a combination of a hexagonal slot and two narrow rectangular slots. After applying scaling non-linear replications (NLR) over the hexagonal slot in both vertical and horizontal directions, the self-triplexing operation with two resonances around 5.23 and 7.50 GHz is reported. For self-triplexing operation, the space inside the hexagonal slot is filled with similar parasitic hexagonal patch and fed by coaxial probe. This generates resonance around 10.82 GHz which can be modelled using the gap between the parasitic patch and hexagonal slot. The independent tuning of each frequency band, isolation and radiation characteristics are also discussed in detail. Finally, the proposed STA is fabricated using standard PCB process and good agreement between the experimental and simulated results is found. The main contributions of the proposed SIW based STA are:

1) To the author’s best knowledge, the proposed SIW-based STA is the first of its kind in the literature where the concept of NLR is utilized for obtaining self-triplexed operation.

2) Easy independent tuning of all the three frequency bands is allowed using scaling of the hexagonal slot in x- and y-directions and spacing (or gap) between the hexagonal parasitic patch and hexagonal slot. Hence, the flexible operation of the proposed STA can be easily utilized for different frequency bands in C- and X-band.

3) The proposed STA is highly compact as compared to already proposed SIW based STAs in the literature [17], [18] which added merit to the proposed design.

4) The orthogonal placement of the feed lines results into the weak coupling between the excitation ports, i.e., better than 43 dB. Therefore, the proposed antenna possesses the highest isolation as compared to existing STAs discussed in [17], [18].

II. PROPOSED ANTENNA DESIGN AND ANALYSIS

Fig. 1 illustrates the proposed SIW-based cavity-backed STA with finely tuned dimensions. The proposed STA design consists of a square SIW-cavity ($W_{CAV} \times L_{CAV}$), a regular hexagonal slot (side length, $S_{slot}$) merged with two rectangular slots (slot-1: $w_{slot} \times L_{arm1}$, slot-2: $w_{slot} \times L_{arm2}$) and orthogonally placed feed lines, each having dimensions of $L_{feed} \times W_{feed}$. The proposed STA uses a 0.787 mm thick RT/Duroid-5880 with a dielectric constant $\varepsilon_r = 2.2$ and a dielectric loss tangent $\tan\delta = 0.0002$.

A. CAVITY DESIGN

The SIW cavity is implemented by scooping out the cylindrical vias of diameter $dv$ and pitch $pv$ from the substrate material used and filled them with the copper. Four rows of
Fig. 2(a) and 2(b), respectively. Similarly, the TE modes are excited at 6.88 GHz and 10.89 GHz as shown in where $d$ sidewalls of the SIW cavity. The value of parameters such metal filled vias around the metallic patch make four sidewalls of the SIW cavity. The value of parameters $d$ and $p$ are chosen maintaining the condition $\frac{dv}{\lambda_0} \leq 0.1$ and $\frac{dv}{pv} \geq 0.5$ (where $\lambda_0$ is the free space wavelength) so as to ensure the negligible power leakage through the SIW cavity sidewalls [25]. The relationship between the resonating frequency of the SIW cavity with its dimensions is given as follows [26]

$$f_{mn} = \frac{1}{2\sqrt{\varepsilon\mu}} \sqrt{\left(\frac{m}{W_{cav,eff}}\right)^2 + \left(\frac{n}{L_{cav,eff}}\right)^2 + \left(\frac{p}{c}\right)^2}$$  \hspace{1cm} (1a)$$

where

$$L_{cav,eff} = L_{cav} - 1.08 \frac{d^2}{pv} + 0.1 \frac{d^2}{L_{cav}}$$  \hspace{1cm} (1b)$$

and

$$W_{cav,eff} = W_{cav} - 1.08 \frac{d^2}{pv} + 0.1 \frac{d^2}{W_{cav}}$$  \hspace{1cm} (1c)$$

where $\varepsilon$ and $\mu$ are the permittivity and permeability of the dielectric material used whereas $m$, $n$ and $p$ are the integers ($=1, 2, 3, \ldots$) and denote the number of variations in the standing wave pattern corresponding to $x$-, $y$- and $z$-axis directions. For a square SIW cavity, i.e., $L_{cav,eff} = W_{cav,eff}$ and $m\neq n$, several orthogonal degenerate modes will start propagating inside the SIW cavity as shown in Fig. 2. When the square SIW cavity is fed with port-1 only (port-2 is terminated by 50$\Omega$ matched load), the $TE_{110}$ and $TE_{120}$ modes are excited at 6.88 GHz and 10.89 GHz as shown in Fig. 2(a) and 2(b), respectively. Similarly, the $TE_{210}$ mode at 10.89 GHz as shown in Fig. 2(c) is excited inside the same cavity when fed from port-2 only (port-1 is terminated by 50$\Omega$ load).

B. SELF-DIPLEXING OPERATION
The hexagonal slot along with the two rectangular slots are not etched exactly at the center of the SIW cavity, i.e., the asymmetric placement of the hybrid-slot divides the whole SIW cavity into two fictitious asymmetric SIW cavities. As a result, two distinct frequency bands centered around 5.23 GHz and 7.50 GHz start resonating inside the SIW cavity when excited individually. Due to loading of the hybrid slot, the original $TE_{110}$ and $TE_{210}$ resonant modes get perturbed and new cavity modes with lower resonant frequency, i.e., at 5.23 and 7.50 GHz are generated. The vector H-field distribution at 5.23 GHz and 7.50 GHz resonating modes are illustrated in Fig. 3(a) and 3(b), respectively. A different current paths are created by $TE_{210}/TE_{120}$ and $TE_{110}$ modes propagating inside SIW cavity due to field concentration near port-1 and port-2, respectively. This results into creation of single transmission zero (TZ) around 7 GHz (as depicted by a dip in the isolation graphs discussed in next sub-sections) which lies between the two resonances, i.e., 5.23 and 7.50 GHz.

C. EFFECT OF NLR AND FREQUENCY TUNABILITY
The concept of NLR was first discussed in [27] where three different NLRs, i.e., elongation, cutting and distortion (or re-grouping) were discussed for obtaining desired flexibility in the radiation pattern of fractal antennas. Reference [28] utilizes elongation NLR on Sierpinski Knopp wide-slot structure for tri-band operation. On similar lines, elongation NLR is applied on the hexagonal slot and its effect of lower and upper resonant frequency is studied. Fig. 4 illustrates a basic NLR steps in a regular hexagon where scaling in $x$- and $y$-directions is regulated by two parameters, namely $x_{scale}$ and $y_{scale}$, respectively. When there is no scaling in any direction, both $x_{scale}$ and $y_{scale}$ takes value equals to 1. With $(x_{scale} > 1, y_{scale} = 1)$ and $(y_{scale} > 1, x_{scale} = 1)$, there will be scaling in $x$- and $y$-directions, respectively.

The operating frequency of the proposed SDA with hybrid slot can be tuned independently by just varying the scaling parameters, i.e., $x_{scale}$ and $y_{scale}$ which makes the design more flexible for SDA operation. Fig. 5(a) illustrates the tuning of

FIGURE 2. Vector H-field distribution of SIW cavity without any slot at (a) 6.88 GHz when only port-1 is ON ($TE_{110}$), (b) 10.89 GHz when only port-1 is ON ($TE_{120}$) and (c) 10.89 GHz when only port-2 is ON ($TE_{210}$).

FIGURE 3. Vector H-field distribution with hybrid slot at (a) 7.50 GHz when only port-1 is ON ($TE_{210}$) and (b) 5.23 GHz when only port-2 is ON ($TE_{110}$).

FIGURE 4. Hexagonal slot showing scaling as NLR in (i) no direction, (ii) $x$-direction only and (iii) $y$-direction only.
7.50 GHz frequency band when \( x_{\text{scale}} \) is varied from 1.0 to 1.4 keeping \( y_{\text{scale}} = 1.0 \). With \( 1.0 \leq x_{\text{scale}} \leq 1.4 \), the resonating second operating frequency is shifted from 7.37 to 7.81 GHz due to decrease in capacitive loading while no significant variation in first operating frequency is noticed. Also, the isolation between the two ports gets from average 44.71 to 50.02 dB with variation in \( x_{\text{scale}} \) from 1.0 to 1.4, respectively.

Similarly, when \( y_{\text{scale}} \) is varied from 1.0 to 1.4, the first operating frequency changes from 5.29 to 5.53 GHz due to decrease in capacitive loading with minimal change in second operating frequency as shown in Fig. 5(b). The average isolation with \( 1.0 \leq y_{\text{scale}} \leq 1.4 \) goes from 44.71 to 49.36 dB.

D. SELF-TRIPLEXING OPERATION

To obtain the self-triplexing operation, a parasitic hexagonal patch (similar to hexagonal slot) is placed concentrically inside the hexagonal slot. This parasitic hexagonal patch is excited by coaxial probe. Due to this configuration, the antenna now able to radiate at three different frequencies. The variation in the gap between the hexagonal patch and similar parasitic patch (or \( g \)) changes the coupling capacitance between them through dielectric region \( (C_{gd}) \) and through air \( (C_{ga}) \) that in turn changes the third resonating frequency around 10.82 GHz. The expressions for coupling capacitances \( C_{gd} \) and \( C_{ga} \) can be given by [29]

\[
C_{gd} = \left( \frac{\varepsilon_r \varepsilon_0}{\pi} \right) \ln \left( \coth \left( \frac{\pi g}{4h} \right) \right) + 0.65c \left[ \frac{0.02}{g/h} \sqrt{\varepsilon_r} + 1 - \frac{1}{\varepsilon_r^2} \right] \tag{2a}
\]

\[
C_{ga} = \frac{1}{2} \varepsilon_0 \frac{K(k')}{K(k)} \tag{2b}
\]

where \( k = \frac{g}{g+2w} \), \( k' = \sqrt{1-k^2} \) and

\[
K(k') = \begin{cases} \frac{1}{\pi} \ln \left( \frac{1 + \sqrt{k'}}{1 - \sqrt{k'}} \right) & 0 \leq k \leq 0.5 \\ \frac{\pi}{\ln[2(1+\sqrt{k})]} & 0.5 \leq k \leq 1 \end{cases} \tag{3}
\]

The independent tuning of the third operating frequency \( (f_{r3}) \) can be explicited by varying the parameter \( g \). The change in \( g \) from 0.5 mm to 2.5 mm brings corresponding shift in \( f_{r3} \) from 10.82 GHz to 13.45 GHz due to increase in coupling capacitances as illustrated in Fig. 6(a). The port-3 exciting the parasitic hexagonal patch is placed asymmetric to both port-1 and port-2 which creates two TZZs (TZ-1 in \( |S_{21}| \) and TZ-2 in \( |S_{21}| \)) which improves the isolation of both port-1 and port-2 with port-3 (see Fig. 6(b)). The vector H-field distribution when the proposed STA is excited with port-3 only (keeping other ports terminated with 50Ω matched load) is shown in Fig. 6(c). It is seen that the proposed STA shows TE110 at 10.7 GHz with maximum intensity at the parasitic hexagonal patch only. In short, the features of the proposed STA can be concluded as following:

1) It operates at three different frequencies, i.e., \( f_{r1} = 5.23 \) GHz, \( f_{r2} = 7.50 \) GHz and \( f_{r3} = 10.82 \) GHz. Independent tuning of the resonating frequencies is also possible.

2) Two TZZs, one near 5.5 GHz in \( |S_{31}| \) and other near 7 GHz in \( |S_{21}| \) are generated due to orthogonal placement of the port-1 and port-2.

3) High isolation (>40 dB) among all the three ports is achieved due to their asymmetric and orthogonal placement with respect to each other.

The graphs showing shift in resonant frequency and their ratio(s) against parameters \( x_{\text{scale}}, y_{\text{scale}} \) and \( g \) affecting resonating frequencies \( f_{r1}, f_{r2} \) and \( f_{r3} \), respectively are plotted.
TABLE 1. Tunable ranges of operating frequencies and supporting applications.

| Parameter Range | Frequency Range (GHz) | Supporting Applications |
|------------------|-----------------------|-------------------------|
| 1.0 ≤ x_{scale} ≤ 1.4 | 7.38 ≤ f_{r1} ≤ 7.81 (Port-1) | LTE/LTE-Advanced, WLAN, and metrological satellite for weather monitoring |
| 1.0 ≤ y_{scale} ≤ 1.4 | 5.29 ≤ f_{r2} ≤ 5.53 (Port-2) | WLAN and Wi-Fi |
| 0.5 ≤ g ≤ 2.5 | 10.82 ≤ f_{r3} ≤ 13.45 (Port-3) | Amateur radio and amateur satellite operations |

FIGURE 7. Variation in resonating frequencies \( f_{r1} \), \( f_{r2} \) and \( f_{r3} \) against parameters (a) \( x_{scale} \), (b) \( y_{scale} \) and (c) gap, \( g \), respectively.

in Fig. 7. This indicates that the each frequency ratios can be adjusted over a certain region as per the requirement.

E. EQUIVALENT CIRCUIT MODEL

Fig. 8(a) portrays the equivalent circuit of the SIW based STA, where each cavity mode is modelled as a parallel combination of \( R, L \) and \( C \) elements. The coupling between the feed and cavity can be modelled as a transformer with a shunt reactance and turns-ratio \( 1:n \). The Circuit Design component of the ANSYS Electronics Desktop software (ver. 17.2) was used for optimizing the equivalent circuit model. The return loss \( (S_{11}) \) of the equivalent circuit model at each resonating frequency is compared with the equivalent circuit model in Fig. 8(b).

III. EXPERIMENTAL VALIDATION

In order to support the idea of SIW-based triple-band STA, a prototype of the proposed antenna is fabricated as shown in Fig. 9(a) and 9(b). The fabricated STA is characterized for validation and tested experimentally as shown in Fig. 9(c) and 9(d). Three low loss connectors are connected and soldered at three excitation ports and the measurement related to return losses \( (S_{11}/S_{22}/S_{33}) \) and isolation \( (S_{21}/S_{31}/S_{32}) \) is performed using Vector Network Analyzer (Agilent Technologies N5247A). The simulated and measured coefficients at all three ports are shown in Fig. 10(a). When excited with port-1, port-2 and port-3 individually (keeping other two ports terminated with 50 \( \Omega \) matched load), the measured (simulated) resonating frequencies \( f_{r1}, f_{r2}, \) and \( f_{r3} \) are 5.33 GHz (5.23 GHz), 7.53 GHz (7.50 GHz), and 11.02 GHz (10.82 GHz) which are in acceptable limits. The isolation between the excitation ports, i.e., \( S_{21}, S_{31}, \) and \( S_{32} \) are also measured which are also found in good agreement with the simulated ones as illustrated in Fig. 10(b).
**TABLE 2.** Performance comparison with existing SIW-based STAs.

| Reference | Physical Size (mm²) | Electrical Size | Resonant frequency (GHz) | Isolation (dB) | Gain (dBi) | FTBR (dB) | Slot shape |
|-----------|---------------------|-----------------|--------------------------|---------------|------------|-----------|------------|
| [17]      | 23×32               | 0.5λ₀           | 7.89/9.44/9.87           | 22.5          | 7.2        | 17.3      | Bow-tie    |
| [19]      | 60×44               | 1.08λ₀          | 4.18/5.2/5.8             | 42/23/7/22.5  | 6.56/4.2/5.85 | 19        | One annular slot and two transverse slots |
| [20]      | -                   | 0.69λ₀          | 3.5/4.8/5.4              | 26            | 4.5/5/6    | 16.1/18.5/22.8 | One annular slot and two transverse slots |
| [21]      | 34.5×29.10          | 0.42λ₀          | 6.53/7.65/9.09           | 19            | 3.1/4.7/3.9 | 13.2      | T-shape    |
| [22]      | 48×48               |                 | 5.6/6.64/6.95            | 23.8          | -          | -         | T-shape    |
| [23]      | 12.6×26.9           | 0.08λ₀          | 4.95/5.3/5.9             | 20.5          | 4.5/4.9/6.1 | 14        | Inverted V-shape |
| [24]      | 32×32               | 0.17λ₀          | 4.14/6.1/8.32            | 30.8/31.4/34.2 | 4.26/4.1/6.27 | 15/16/20 | Modified I-shape |
| [18]      | -                   |                 | 6.77/8.57/13.37         | 15.6/23/17    | 4.67/5.15/5.8 | 14        | Dumbbell shape |
| **This work** | **29×29**          | **0.25λ₀**      | **5.23/7.50/10.82**      | **43.27/47.84/45.17** | **7.33/6.66/6.28** | **25.46/28.17/32.59** | **NLR hexagonal patch with two rectangular narrow slots** |

**FIGURE 9.** Fabricated prototype of the proposed STA (a) front side, (b) back side, (c) testing during VNA and (d) inside anechoic chamber for gain/efficiency and radiation pattern measurement.

**FIGURE 10.** Comparison of simulated (solid line) and measured (dashed line) (a) reflection coefficient and (b) S₂₁ (red), S₃₁ (blue), S₃₂ (green).

The gain and far-field measurement are performed inside the anechoic chamber with measurement setup as shown in [Fig. 11](a).

**FIGURE 11.** (a) Gain and radiation pattern measurement set-up sketch and (b) measured gain/efficiency of the triplexing antenna.

The gain and far-field measurement are performed inside the anechoic chamber with measurement setup as shown in Fig. 11(a). The measured (simulated) peak gain values are 7.33 (7.65) dBi, 6.66 (6.93) dBi, and 6.28 (6.74) dBi at lower band, middle band, and upper frequency bands, respectively as reported in Fig. 11(b). It is noted that gain within a particular frequency band is obtained by applying excitation at only one port while terminated other two ports with matched 50Ω. The slight variations between simulated and measured values can be attributed to the soldering joints, uncontrolled dielectric losses, and fabrication imperfections.
TABLE 3. Simulated and (measured) results of proposed STA.

| Parameters          | Excitation Port |
|---------------------|-----------------|
|                     | Port-1 | Port-2 | Port-3 |
| Resonating frequency (GHz) | 5.33 (5.28) | 7.53 (7.48) | 11.02 (10.81) |
| 10 dB bandwidth (MHz)    | 30 (47) | 71 (69) | 310 (304) |
| Isolation (dB)           | >40     | >40     | >40     |
| Gain (dBi)               | 7.33 (7.65) | 6.66 (6.93) | 6.28 (6.74) |
| FTBR (dB)               | 25.46   | 28.17   | 32.59   |
| Efficiency (%)          | 97.39   | 95.82   | 97.83   |

IV. CONCLUSION

A compact SIW cavity backed antenna with enhanced self-triplexing property is presented. The designed antenna supports operation in three different frequency bands, i.e., 5.23, 7.50 and 10.82 GHz simultaneously. The proposed design comprised of single SIW cavity loaded with hexagonal slot merged with two rectangular narrow slots. Initially, the fundamental TE$_{110}$ mode along with two degenerated TE$_{120}$ and TE$_{210}$ modes are excited inside the SIW cavity with the help of orthogonally placed microstrip feed lines. Due to slot loading, the fundamental mode along with degenerate modes shift towards lower frequency, leading to overall size compactness of 68% as compared to [19]. Up to this stage, the proposed design supports two frequency bands centered around 5.23 and 7.50 GHz. For self-triplexing operation, a parasitic patch (similar to hexagonal slot) is placed concentrically inside it. This enabled the antenna to work in 10.82 GHz frequency band as well. The proposed self-triplexing antenna allows independent tuning of all three frequency bands using a single parameter/variable. High isolation among the excitation ports (>40 dB), good gain level (>6 dBi), high FTBR (>25 dB), and compact size ($0.25\lambda_o$) make the proposed triplexer a preferable candidate for both C- and X-band applications including WLAN/5G/WiMAX/Wi-Fi, amateur radio and satellite operations.

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AMIT KUMAR SINGH received the Ph.D. degree from IIT (BHU), Varanasi, in 2010. He has been working as an Associate Professor with the Electronics Engineering Department, IIT (BHU), since 2012. He has published and coauthored over 70 journal articles and conference papers. His research interests include the areas of design of millimeter frequency antennas, feeds for parabolic reflectors, dielectric resonator antennas, microstrip antennas, EBG, artificial magnetic conductors, soft and hard surfaces, antennas for RFIDds, phased array antennas, and computer aided design for antennas.