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Implementation of highly isolation OLR: based microstrip full-duplex Tx/Rx antenna systems with low insertion loss for contemporary wireless system applications

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Abstract

This paper presents a Highly Isolation open-loop resonators (OLR)—based microstrip full-duplex Tx/Rx antenna systems with low insertion loss for contemporary wireless system applications. Through a T-junction combiner, the proposed diplexer is accomplished by combining two OLR—based band-pass filters tuned at two distinct frequencies. The system is implemented on a Rogers TMM4 substrate with a loss tangent of 0.002, a dielectric constant of 4.7, and a thickness of 1.52 mm. The suggested full duplex has dimensions of (90 × 70) mm². It achieves a modest frequency space ratio of R = 0.1646 in both transmit and receive modes by having two resonance frequencies of $f_t = 2.191$ GHz and $f_r = 2.584$ GHz, respectively. The simulated structure displays good insertion losses (IL) of approximately 1.2 dB and 1.79 dB for the two channels, respectively, at fractional bandwidths of 1.24% at 2.191 GHz and 0.636% at 2.584 GHz. The simulated isolation values for 2.191 GHz and 2.584 GHz are 53.3 dB and 66.5 dB, respectively.

Keywords: Band-pass filter (BPF), Selectivity, Open-loop resonator (OLR), Full duplex, Insertion loss (IL)

1 Introduction

Many wireless system applications depend on wireless communication technologies, which are becoming an essential component of daily life [1]. There are many techniques to increase capacity such as multiple input multiple output (MIMO) [2–9] and Discrete wavelet transforms (DWT). DWTs are employed in orthogonal frequency division multiplexing (OFDM) systems to improve spectral efficiency. Therefore, wavelet transforms can be used to design antenna diversity scheme to improve performance of system and spectrum efficiency [10–15].

Similar to that, a full-duplex transceiver is a crucial kind of communication that need extra study attention. In a full-duplex transceiver system, employing a single antenna for both signal transmission and reception may be more economical than using two separate antennas. However, it needs excellent selectivity, low insertion loss, and good ports



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isolation [16]. Multiplexing, in general, is the act of combining many signals over a single communication channel in a variety of ways (including time, space, code, frequency, etc.). In order to ensure that only signals of the right frequency may access each chain, frequency domain multiplexing, also known as duplexing, requires the employment of high-isolation filter circuits between the antenna and the transmit/receive (Tx/Rx) signal chains [17].

Diplexers are three-port devices. Two independent channels that operate at two different desired frequencies are created by the diplexer devices by splitting the input signal from a single input port [18, 19]. Various varieties of microstrip diplexer are introduced in [20-36]. They all, however, take up a lot of room. Developed for high isolation in [20] is a cavity-backed self-diplexing Y-shaped slot antenna with a quarter-mode substrate integrated waveguide (QMSIW). The rectangular substrate integrated waveguide (SIW) is given two unequal radiating apertures for radiation at 3.9 GHz and 4.9 GHz by inserting a Y-shaped slot on the top side. A high-gain antenna is provided by this structure, however it has poor Tx-Rx isolation (34 dB) and a high-frequency space ratio (r=0.227). A self-diplexing bow-tie-shaped slot antenna with a SIW cavity as its foundation is introduced in [21]. Two different feed lines are used to activate the SIW cavity, which then resonates at the transmitting and receiving frequencies. Using this wellknown design, a high-gain antenna with a unidirectional radiation pattern is produced. However, it has a poor Tx-Rx isolation of 22 dB and a low high-frequency space ratio of r = 0.22. In [22], a microstrip diplexer is used to integrate the wireless local area network (WLAN) and global system for mobile (GSM) bands. This design lessens the drawbacks of the microstrip diplexer. Its drawbacks include a 30 dB isolation limit and substantial channel losses [23]. Proposes a simple approach for building a microstrip diplexer. It is constructed by joining two tiny Square Open-Loop Resonator band-pass filters. For 2.45 GHz Radio Frequency Identification applications, these filters were developed. It makes advantage of Chebyshev's approximation. 40 dB is the diplexer isolation. In [24], a substrate integrated waveguide (SIW) diplexer with dual-mode resonators is proposed. The performance of the RF front end is improved by this diplexer. This diplexer offers suitable isolation of 49 dB and 53 dB for the broadcast and receive channels, respectively. But its size is one of its drawbacks. The development of a squared open-loop resonator (SOLR)-based microstrip diplexer is suggested in [25]. The proposed diplexer achieves a negligibly small frequency space ratio of R = 0.114 and has two resonance frequencies for the transmit and receive channels, respectively, of 1.81 GHz and 2.03 GHz. But its size is one of its drawbacks.

Shaheen et al.[26] Combines two different channel filters to form a dual-band bandpass filter, which is then used to construct a microstrip diplexer. In contrast to the traditional design approach, which requires separate connections or junctions for energy distribution, this design eliminates the need for external connectors when building diplexers. Both modeling results and experimental findings demonstrated a 50 dB isolation between the diplexer's broadcast and receive bands. However, it did had sizable insertion losses of 2.88 dB and 2.95 dB in the transmit and receive bands, respectively. In [27], a novel microstrip diplexer with excellent isolation and selectivity was introduced.

It is based on merging two compact bandpass filters for LTE applications made up of open/shorted lines and an open stub. Many different resonator types are employed [28–38] to enhance frequency response performance. Other resonator forms, such U-shaped [28] and T-shaped [27], have recently been developed. Pi-shaped [21], stepped-impedance [22], and Patch [23, 24] resonators. In [33], patch resonators are used to provide a filtering response. Two bandpass filters (BPFs) consisting of spiral cells and linked lines are combined in [36] to form a microstrip diplexer.

It has various shortcomings, such as undesirable harmonics and significant channel losses. Although the configuration of the exhibited microstrip diplexer in [37] uses three connected lines structures to minimize harmonics more effectively, the problem of significant losses at both channels remains. Although efforts are being made to produce a small, effective microstrip bandpass diplexer, design considerations including minimal losses and enhanced fractional bandwidth make it difficult to forgo the small size.

It is important to note that the suggested duplexer and diplexer systems are implemented on a Rogers TMM4 substrate with a relative dielectric constant of 4.5 and a thickness of 1.52 mm. The computer simulation technology (CST) microwave studio software package (CST-MWS-2019) is used to run the simulations. From a practical perspective, the suggested duplexer is produced, its scattering characteristics are experimentally measured, and it is discovered that they perfectly match the modeling results.

This paper's summary is structured as follows. The Methods and experiment is presented in Sect. 2. In Sect. 3, Results and discussion are presented. Section 4 served as the paper's conclusion.

2 Method and experiment

2.1 Design of the suggested antenna element

The CST design processes, prototype construction, and experimental measurements of a novel wideband circular-shaped antenna element are presented in this part. The suggested antenna construction consists of a ground plane with square notch loading, four semi-squared stubs, and a circular radiating patch. Figure 1 depicts the planned antenna element's final geometrical structure. Calculated by [20] is the initial value of the circular patch radius:



Fig. 1 Geometrical structure of the proposed circular-shaped wideband antenna element; **a** top view, **b** bottom view



Fig. 2 Simulated reflection coefficient |s11| of the proposed wide band antenna

Table 1 Dimensions of the proposed circular-shaped wideband antenna element in (mm)

Parameter	Value (mm)	Parameter	Value (mm)	
W _{ant}	25	R _{ant}	7	
L _{ant}	35	$W_{\rm sant}$	2.5	
W _{notch}	3	L _{sant}	2	
L _{notch}	1	$W_{\rm fant}$	2.04	
Lgant	13.6	L _{fant}	14	

$$R = \frac{G}{\left\{1 + \frac{2h}{\pi \varepsilon_r G} \left[\ln\left(\frac{\pi G}{2h}\right) + 1.7726\right]\right\}^{1/2}}$$
(1)

$$G = \frac{8.791 \times 10^9}{f_r \varepsilon_r} \tag{2}$$

where R = The radius of the circular radiating patch in cm. h = The thickness of the substrate in cm. ε_r = The relative dielectric constant of the substrate. f_r = The required resonance frequency.

While, the CST simulator optimization is used to calculate the ideal value of the circular patch radius. With large return losses around the 3 GHz frequency, as shown in Fig. 2, this arrangement offers a broad operating frequency spectrum from 1.3 to 4 GHz. This is caused by an abrupt variation in impedance at the point where the feed line and the radiating patch converge. In order to increase the electrical length of the radiating patch, improve the bandwidth, and achieve better impedance matching across the entire frequency range, a square slit is etched on the top side of the partial ground plane and two square stubs are added underneath the circular radiating patch on both sides of the feeding line.

As shown in Fig. 2, the final structure reduced antenna return loss in the operating frequency range of 1.3–4 GHz with a scattering parameter of $-48\text{dB} \le |s_{11}| \le -14\text{dB}$. Table 1 provides the ideal dimensions of the suggested antenna construction. The antenna has a total size of $(25 \times 35)\text{mm}^2$ and is printed on a Rogers TMM4 substrate with a thickness of 1.52 mm and a relative dielectric constant of 4.5.



Fig. 3 Simulated gain of the proposed wide band antenna



Fig. 4 Simulated radiation efficiency of the proposed wide band antenna

The achieved antenna gain vs frequency is displayed in Fig. 3 when the suggested antenna design structure is taken into account. Over the operational frequency range of 1.3–GHz, the antenna offers a significant gain of between 1.6 dBi and 4.7 dBi. Additionally, as demonstrated in Fig. 4, it has good radiation efficiency across the working frequency range of 1.3–4 GHz, ranging from 89 to 98.8%.

The simulated radiation patterns of the proposed antenna element are presented in this section at the desired frequencies. Figure 5a, and b show the 3D radiation patterns of the antenna at the transmit frequency $f_t = 2.51$ GHz and the receive frequency $f_r = 2.81$ GHz, respectively. The antenna provides a nearly omnidirectional radiation pattern in the H-plane and a dipole-like radiation pattern in the E-plane as shown below. Figure 5c and d shows the polar plot of the antenna radiation patterns at $\varphi = 90^{\circ}$ for $f_t = 2.51$ GHz and $f_r = 2.81$ GHz, which are looks like the dipole-like radiation pattern in the E-plane. It also lists the pattern characteristics in terms of main lobe



Fig. 5 3D radiation pattern of proposed antenna at $\mathbf{a}_{t} = 2.51 \text{ GHz}$. $\mathbf{b}_{fr} = 2.51 \text{ GHz}$, 2D radiation pattern at $\varphi = 90^{\circ}$ for $\mathbf{c}_{t} = 2.51 \text{ GHz}$. $\mathbf{d}_{fr} = 2.51 \text{ GHz}$, and 2D radiation pattern at $\theta = 90^{\circ}$ for $\mathbf{e}_{t} = 2.51 \text{ GHz}$. $\mathbf{f}_{r} = 2.51 \text{ GHz}$, and

magnitude, main lobe direction, and angular width. Figure 5e and f shows the polar plot and characteristics of the antenna radiation patterns at $\theta = 90^{\circ}$ for $f_t = 2.51$ GHz and $f_r = 2.81$ GHz, which are looks like the dipole-like radiation pattern in the E-plane.

2.2 Design of the transmit and receive BPFs

We present the transmit and receive bandpass filters (BPFs) in this section. Figure 6 depicts the suggested architecture for the microstrip bandpass filter. It is clear that this construction consists of a standard rectangular open-loop resonator and two input/out-put feed lines. The gap g1 achieves coupling between the two transmission lines and the



Fig. 6 Geometrical construction of the OLR-based transmit BPF with resonance frequency $f_t = 2.191$ GHz. **a** Top view; **b** Bottom view



Fig. 7 Receive BPF's simulated S-parameters

resonator; whereas, the gap Lf splits the two feed lines. The folded microstrip resonator in this case and the effective positioning of the two feed lines ensure a superior size reduction. The CST-MWS-2019 model, which is printed on a 1.52 mm Rogers TMM4 substrate, was utilized to replicate the OLR-BPF and examine how the BPF functions.

At the transmit frequency of $f_t = 2.191$ GHz, OLRs are used, as shown in Fig. 7a and b, each with a total length of roughly $\lambda_g/2$. Table 2 contains a list of the filter's dimensions. The width and length of the trace line, coupled with the separation gap g_1 , determine each resonator's internal capacitance, which in turn influences the filter's selectivity and insertion loss. Figure 7 shows the simulated scattering parameters of the suggested transmit BPF, obtained using the CST Microwave Studio. The BPF has a center frequency of 2.191 GHz, a 3 dB bandwidth of 47.1 MHz, a fractional bandwidth of 1.24%, a return loss of 20 dB, and an insertion loss of 1.4 dB, meeting several specifications. The suggested receive BPF, which has dimensions indicated in

Parameter	Value (mm)	Parameter	Value (mm)	
W	25	L _{s1}	11.2	
L	25	<i>g</i> ₁	0.75	
W _f	3.06	<i>g</i> ₂	1.5	
Lf	2.5	g_3	1	
Ws	7	g_{s1}	0.75	
Ls	14	g_52	1.75	
W _{s1}	7	q_{s3}	1	

 Table 2
 Suggested transmit and receive BPF's dimensions



Fig. 8 Geometrical construction of the OLR-based receive BPF with resonance frequency $f_t = 2.584$ GHz. **a** Top view; **b** Bottom view



Fig. 9 Transmit BPF's simulated S-parameters

Table 2, is depicted in Fig. 8 and follows the same conceptual framework. Figure 9 displays the receive BPF's simulated scattering parameters. The curves' analysis reveals the BPF's center frequency to be 2.584 GHz, 3 dB bandwidth to be 20.7 MHz,



Fig. 10 Structure of proposed full-duplex Tx/Rx antenna system: a top view and b bottom view

Table 3 Realized specifications of the proposed Tx/Rx antenna system

Specifications	Тх	Rx
Size (mm ²)	(100 × 70)mm ²	
f ₀	$f_t = 2.191 \text{GHz}$	$f_r = 2.584 \text{GHz}$
FBW (%)	1.21%	1.7%
Reflection coefficient (dB)	$ s_{11} = -21$ dB	$ s_{22} = -22 dB$
Ports isolation (dB)	—32dB	-41dB

fractional bandwidth to be 0.636%, return loss to be 15.6 dB, and insertion loss to be 1.3 dB.

2.3 Design of the proposed duplexer

The fundamental function of a duplexer is to send signals from the transmitter to the antenna and from the antenna to the receiver, which is accomplished with success in the antenna system that is presented. The suggested full-duplex Tx/Rx patch antenna system's structure is introduced in this section. Based on the integration of the proposed broad band antenna described in Sect. 1 and the BPFs in Sect. 3, as seen in Fig. 10, it is used.

The antenna feeding transmission line is connected to the feeding port #1 of the diplexer; while, the other ports #3 and #2 are set for transmission and reception modes, respectively. The duplexer system is realized on a Rogers TMM4 substrate having a thickness h = 1.52 mm, relative dielectric constant $\varepsilon_r = 4.5$, and loss tangent $\delta = 0.002$ with overall size of (90 mm × 70 mm × 1.52 mm). The design is proceeded using CST microwave studio software package 2019. Table 3 shows that The realized specifications of the proposed Tx/Rx antenna system.

3 Results and discussion

Figure 11 shows the simulated scattering parameters of the proposed Tx/Rx antenna system, where the transmit and receive frequencies are $f_t = 2.191$ GHz and $f_r = 2.584$ GHz, respectively. The simulated isolations between the two ports of the antenna at f_t are -32dB and at f_r are -41dB (Fig. 12).

The fabricated prototype of the proposed Tx/Rx antenna system is shown in Fig. 13. The scattering parameters of the system are measured using the Rohde & Schwarz ZVB 20 vector network analyzer as shown in Fig. 14. The measured resonant frequencies at



Fig. 11 Simulated S-Parameters of the proposed Full duplex antenna system



Fig. 12 Distribution of surface current in the suggested full-duplex antenna system at $\mathbf{a} f_t = 2.191 \text{ GHz}$, and $\mathbf{b} f_t = 2.584 \text{ GHz}$

transmitting and receiving ports are $f_t = 2.191$ GHz and $f_r = 2.584$ GHz, respectively. The measured isolation between the two input ports are below -32 dB and -35 dB at $f_t = 2.191$ GHz and $f_r = 2.584$ GHz, respectively, which are higher than the simulated values of -32 dB and -41 dB, respectively. A good agreement between the simulated and measured results are observed. However, there is a small difference between the simulated and measured results due to fabrication tolerance values.

With regard to size, resonance frequency (GHz) at the transmit and receive channels, fractional bandwidths (FBW (GHz)), insertion loss (dB), return loss (dB), isolation (dB), and frequency space ratio (R), the proposed full duplex performs better than those ranked #1 through #10. A comparison of the available diplexer designs, which are listed in Table 4, shows a competitive variant.

4 Conclusion

This study introduces effective full-duplex antenna system designs with excellent isolations and minimal insertion losses. The suggested diplexer is realized by merging two OLR-based band-pass filters adjusted at two different frequencies using a T-junction combiner. At the transmit frequency $f_t = 2.191$ GHz and the receive frequency $f_r = 2.584$ GHz, respectively, the fractional bandwidths are the same and equal 2.5%, and the insertion losses are -1.2 dB and -1.7 dB, respectively. The planned broad



Fig. 13 Fabrication of the final proposed Tx/Rx antenna system **a** top view, **b** bottom view, and **c** the measurement using the Rohde & Schwarz ZVB 20 vector network analyzer



Fig. 14 Measured and simulated S-Parameters of the proposed Full-duplex antenna system

band antenna with partial ground and suggested diplexer were combined to create an effective full-duplex Tx/Rx antenna system. Between the two transceiver ports, it obtained remarkable isolation, reaching -32 dB at 2.191 GHz and -41 dB at 2.584 GHz. Additionally, it obtained a low frequency space ratio of r=0.1646. Furthermore, the compactness of the proposed antenna makes it attractive for practical applications. Selectivity, Open-loop resonator (OLR), Full duplex, and Insertion loss (IL).

References	Size λ_g^2	Freq. (GHz)	FBW (%)	Insertion Loss (dB)	Return loss (dB)	Isolation (dB)	R
[5]	0.0233	1.7/3.3	1.8	0.87	- 36	- 23/ - 25	0.64
[7]	0.6889	3.9/4.9	NA	NA	- 32/ - 38	- 34	0.227
[8]	0.4356	9/11.2	NA	NA	- 28/ - 32	- 25	0.22
[9]	0.35	1.8/2.4	6/5.8	NA	- 23/ - 25	30	0.286
[10]	1.2	2.2/2.6	4.55/5	1.6/1	- 20	40	0.167
[11]	4.6	8.04/9.07	4.23/4.19	2.35/2.33	- 22/ - 30	49/53	0.12
[12]	1.5	1.81/2.03	2.25/3	1.98/1.9	- 30/ - 38	58/46	0.114
[14]	0.167	1.8/2.1	5.5/6.2	2/1.8	- 28/ - 30	40	0.154
[22]	0.89	1.85/2.5	NA	4.2/3.3	-20/-19	31	NA
[23]	0.98	1.41/2.02	NA	4.4/4.6	- 32/ - 31	29	NA
Proposed work	0.435	2.191/2.584	1.24/0.636	1.2/1.79	-21/-21.9	- 32/ - 41	0.1646

Table 4 Comparison with related work

Abbreviations

 BPF
 Band-pass filter

 OLR
 Open-loop resonator

 IL
 Insertion loss

 SIW
 Substrate integrated waveguide

 QMSIW
 Quarter-mode substrate integrated waveguide

 WLAN
 Wireless local area network

 GSM
 Global system for mobile

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Author contributions

Authors contributed to the preparation of this manuscript. Authors conceived the original ideas presented in this work. Additionally, authors has cooperated writing this manuscript and review all parts of it. Finally, other has been equally contributed in this work.

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Availability of data and materials

The experimental data used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication All authors agree to publish the research in this journal.

Competing interests

The authors declares no competing interests.

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References

- 1. Z. Jiayu, Q. Deli, Q. Haifeng, Virtual full-duplex buffer-aided relay selection schemes for secure cooperative wireless networks. J. Wirel. Com. Net. (2022). https://doi.org/10.1186/s13638-022-02127-1
- R.H. Elabd, A.J.A. Al-Gburi, SAR assessment of miniaturized wideband MIMO antenna structure for millimeter wave 5G smartphones. Microelectron. Eng. 282, 112098–112115 (2023). https://doi.org/10.1016/j.mee.2023. 112098

- R.H. Elabd, H.H. Abdullah, A high isolation UWB MIMO Vivaldi antenna based on CSRR-NL for contemporary 5G millimeter-wave applications. J. Infrared Milli. Terahz Waves 43, 920–941 (2022). https://doi.org/10.1007/ s10762-022-00894-y
- R.H. Elabd, H.H. Abdullah, M. Abdelazim, Compact highly directive MIMO vivaldi antenna for 5G millimeter-wave base station. J. Infrared Milli. Terahz Waves 42, 173–194 (2021). https://doi.org/10.1007/s10762-020-00765-4
- R.H. Elabd, H.H. Abdullah, M. Abdelazim, A. Abo talb, A. Shaban, Studying the performance of linear precoding algorithms based on millimeterwave MIMO communication system. Int. J. Sci. Eng Res. 10(1), 2076–2082 (2019)
- R.H. Elabd, H.H. Abdullah, M. Abdelazim, A. Abotalb, A. Shaban, Low complexity high-performance precoding algorithms for mm-wave MU-MIMO communication system. Wirel. Pers. Commun. (2020). https://doi.org/10. 1007/s11277-020-07692-6
- R.H. Elabd, A.H. Hussein, Efficient design of a wideband tunable microstrip filtenna for spectrum sensing in cognitive radio systems. J. Wirel. Com. Net. 109, 2023 (2023). https://doi.org/10.1186/s13638-023-02321-9
- R.H. Elabd, Compact dual-port MIMO filtenna-based DMS with high isolation for C-band and X-band applications. J. Wirel. Com. Net. (2023). https://doi.org/10.1186/s13638-023-02319-3
- A.A. Kabeel, A.H. Hussein, A.E. ElMaghrabi, R.H. Elabd, Design of a circular concentric microstrip patch antenna array for WI-FI band energy harvesting. J. Eng. Res. 7(5), 156–159 (2023)
- R. Guido, F. Pedroso, R. Contreras, L.C. Rodrigues, E. Guariglia, J.S. Neto, introducing the discrete path transform (DPT) and its applications in signal analysis, artefact removal, and spoken word recognition. Dig. Sig. Process. 117(1), 103158 (2021)
- 11. E. Guariglia, S. Silvestrov, Fractional-wavelet analysis of positive definite distributions and wavelets on D'(C), in *Engineering Mathematics II*, Springer, pp. 337–353, (2016)
- 12. L. Yang, H.Su, C. Zhong, Z. Meng, H. Luo, X. Li, Y.Y. Tang, Y. Lu, Hyperspectral image classification using wavelet transform-based smooth ordering. Int. J. Wavelets Multiresolut. Inf. Process, 17(6), (2019).
- 13. E. Guariglia, Harmonic Sierpinski gasket and applications. Entropy 20(9), 714 (2018)
- X. Zheng, Y.Y. Tang, J. Zhou, A framework of adaptive multiscale wavelet decomposition for signals on undirected graphs. IEEE Trans. Signal Process. 67(7), 1696–1711 (2019)
- E. Guariglia, Entropy and fractal antennas. Entropy 18(3), 1–17 (2016)
- L. Zhou, W. Zhou, Y. Sun, Y. Han, J. Jiang, D. Zhang, Design of high-order resonator HTS diplexer with very different FBW. Electronics (2023). https://doi.org/10.3390/electronics12030691
- G.L. Matthaei, E.G. Cristal, Multiplexer channel-separating units using interdigital and parallel-coupled filters. IEEE Trans. Microw. Theory Tech. 13(3), 328–334 (1965)
- R.J. Wenzel, Printed-circuit complementary filters for narrow bandwidth multiplexers. IEEE Trans. Microw. Theory Tech. 16(3), 147–157 (1968)
- S. Roshani, S.I. Yahya, Y.S. Mezaal, M.A. Chaudhary, A.A. Al-Hilali, A. Mojirleilani, S. Roshani, Design of a compact quad-channel microstrip diplexer for L and S band applications. Micromachines 14, 553 (2023). https://doi.org/ 10.3390/mi14030553
- C.G. Abdessamed, Review on technologies used to design RF diplexers. Int. J. Biosen. Bioelectron. 4(1), 23–25 (2018)
- 21. A.A. Ayman, Design of highly compact self-diplexing Y-shapedslot antenna employing quarter-mode substrate integrated waveguide. Int. J. RF Microw. Comput. Aid. Eng. (2021). https://doi.org/10.1002/mmce.22827
- 22. S. Mukherjee, A. Biswas, Design of self-diplexing substrate integrated waveguide cavity backed slot antenna. IEEE Antennas Wirel. Propag. Lett. **15**, 1775–1778 (2016)
- W. Feng, X. Gao, W. Che, Microstrip diplexer for GSM and WLAN bands using common shorted stubs. Electron. Lett. 50, 1486–1488 (2014). https://doi.org/10.1049/el.2014.2500
- H. Tizya, F. Riouch, A. Tribak et al., Microstrip diplexer design based on two square open loop bandpass filters for RFID applications. Int. J. Microwave Wire. Technol. 10(4), 412–421 (2018). https://doi.org/10.1017/S175907871 8000314
- F. Cheng, C. Gu, B. Zhang et al., High isolation substrate integrated waveguide diplexer with flexible transmission zeros. IEEE Microwave Wirel. Compon. Lett. 30(11), 1029–1032 (2020)
- M. M. Shaheen, N. M. Mahmoud, A. Alim, M. E. Nasr, A. H. Hussien, Implementation of a highly selective microstrip diplexer with low insertion loss using square open-loop resonators and a T-junction combiner. Radioengineering, 31 (2022)
- A.O. Nwajana, K.S.K. Yeo, Microwave diplexer purely based on direct synchronous and asynchronous coupling. Radioengineering 25, 247–252 (2016). https://doi.org/10.13164/re.2016.0247
- W. Feng, M. Hong, W. Che, Microstrip diplexer design using open/shorted coupled lines. Electromagn. Res. Lett. 59, 123–127 (2016). https://doi.org/10.2528/PIERL16030805
- G. Karimi, A. Lalbakhsh, K. Dehghani, H. Siahkamari, Analysis of novel approach to design of ultra-wide stopband microstrip low-pass filter using modified u-shaped resonator. ETRI J. 37, 945–950 (2015)
- A. Lalbakhsh, M.U. Afzal, K.P. Esselle, S.L. Smith. An array of electromagnetic bandgap resonator antennas for V-band backhaul applications, in *Proceedings of the IIER International Conference (248th: 2019), Tokyo, Japan, 7–8 August 2019, The International Institute of Engineers and Researchers: Tokyo*, pp. 69–71, (2019)
- H. Sariri, Z. Rahmani, A. Lalbakhsh, S. Majidifar, Compact LPF using T-shaped resonator. Frequenz 67, 17–20 (2013)
- 32. Z. Wang, C.W. Park. Multiband pi-shaped structure with resonators for tri-band Wilkinson power divider and tri-band rat-race coupler, in Proceedings of the 2012 IEEE/MTT-S International Microwave Symposium Digest, Montreal, QC, Canada, 17–22, pp. 1–3, (2012).
- K. Dehghani, G. Karimi, A. Lalbakhsh, S.V. Maki, Design of lowpass filter using novel stepped impedance resonator. Electron. Lett. 50, 37–39 (2014)
- Q. Zhang, G. Zhang, Z. Liu, W. Chen, W. Tang, Dual-band filtering power divider based on a single circular patch resonator with improved bandwidths and good isolation. IEEE Trans. Circ. Syst. II Express. Briefs 68, 3411–3415 (2021)

- S. Chen, S. Qi, X. Chen, G. Sun, W. Wu, Five-way radial filtering power divider using back-to-back quarter-mode substrateintegrated waveguide and microstrip resonator. Electron. Lett. 57, 888–890 (2021)
- H.A. Hussein, Y.S. Mezaal, B.M. Tseng, Miniaturized microstrip diplexer based on fr4 substrate for wireless communications. Elektronika Ir Elektrotechnika 27(5), 34–40 (2021)
- C.F. Chen, K.W. Zhou, R.Y. Alameri, H.Y. Chen, Y.H. He, T. Seng, W.J. Liu, J.H. Weng, Design of microstrip multifunction integrated diplexers with frequency division, frequency selection, and power division functions. IEEE Access. 9, 53232–53242 (2021)
- S.I. Yahya, A. Rezaei, L. Nouri, Compact wide stopband microstrip diplexer with flat channels for WiMAX and wireless applications. IET Circ. Dev. Syst. 14(6), 846–852 (2020)

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