T-Junction Diplexer for RF Front End of a Cellular Base Station

Augustine O. Nwajana[1]*, Patrick U. Okafor[2] and Stella N. Arinze[2]

[1]School of Engineering, University of Greenwich, Medway Campus, Kent ME4 4TB, United Kingdom
[2]Dept. of Electrical/Electronic Engineering, Enugu State University of Sci. & Tech., Enugu Nigeria
E-mail: a.nwajana@ieee.org

***Abstract*- A sixth order high isolation diplexer with Chebyshev channel filter characteristics is presented. The diplexer is proposed for isolating the transmit (Tx) and the receive (Rx) frequencies within the front end of a cellular base station. A novel formulation for achieving the T-junction used in distributing energy between the Tx and Rx channels is proposed. The formulation is based on the electrical length of transmission lines, and the guided-wavelength of the lines at one giga-Hertz frequency. The proposed formulation would help design engineers eliminate the uncertainties associated with repeated tuning and optimisation of T-junctions to achieve the desired energy distribution in diplexer designs. A test diplexer with Tx and Rx frequencies of 2.6 GHz and 3.0 GHz, respectively, have been designed, simulated, and presented. The design implementation is based on Rogers RT/Duroid 6010LM substrate with a 10.7 dielectric constant and 1.27 mm thickness. The circuit model and microstrip layout results of the diplexer show good agreement with a high isolation of better than 50 dB between the Tx and the Rx channels. The in-band minimum insertion loss is better than 1.1 dB, with a greater than 20 dB in-band return loss across both the Tx and the Rx bands.**

***Index Terms*- diplexer, filter, coupling, resonator, hairpin, microstrip, T-junction.**

I. INTRODUCTION

Modern radio frequency (RF) front end of cellular base-stations require various components to ensure adequate functionality as shown in Fig.1 [1]. The diplexer in Fig.1 is very essential as it plays an important role in reducing the size, weight, and even cost of operating a cellular base-station. This is because a diplexer makes it possible for the use of a single transmission line component and a single antenna device to both transmit and receive signals simultaneously. This benefit of the diplexer has led to a growing interest in its design as a way of improving the performance of modern communication systems. A very good practical application of diplexers in satellite communication systems is in space crafts, where the mass and volume of the space craft can be considerably reduced as a diplexer is used to transmit and receive signals through a single antenna [2].

Diplexers, as the simplest form of multiplexers, are generally used for either splitting a wide frequency band into two narrow sub-bands, or for combining two narrow sub-bands into a single wide-band frequency [3]. As a frequency selective device, a diplexer connects two different networks (e.g. channel filters) with varied operating frequencies to a single port device (e.g. antenna port). As shown in Fig.1, the diplexer is an important component in the entire communication system. It is composed of two bandpass (or channel) filters and a power divider/combiner. The Tx and the Rx filters respectively allows for the transmission and the reception of signals through the single antenna. The Tx filter is designed to have high power handling capability due to the relatively high-power signals generated at the transmitter. The Rx filter, however, is designed to handle very weak signals from the receiver, hence, no power handling consideration is needed at the Rx channel. One characteristic that must be in the forefront when designing a diplexer is the isolation between the Tx and the Rx channels. A poor isolation between the Tx and the Rx channels would lead to a large amount of power being deflected towards an undesired direction during the diplexer operation. For example, transmit signals to receive path and vice versa [1]. The selectivity of the transmit and the receive channels of a diplexer is another vital design criterion that should be put into consideration.

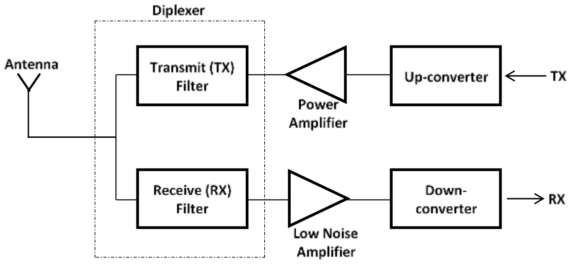


Fig.1. RF front end of a cellular base-station.

Diplexers are typically made up of two separately designed channel filters with a three-port impedance matching network as shown in Fig.2. The two channel filters are distinctly designed to operate at different frequencies that relate to the frequencies of the Tx and the Rx channels of the diplexer. The combining network, i.e. the 3-port impedance matching network, is normally designed to produce good transmission in one passband and exhibit high impedance in the other passband [4]. This rigorous design condition of the 3-port impedance matching network is to enable the attainment of the desired channel isolation. According to [5], designing a matching network that can produce a good transmission in one passband and a good attenuation in the other passband is very challenging. The performance of a diplexer will highly depend on the channel filters, as well as the three-port matching network [6]. This is because the overall losses experienced in the diplexer are due to the sum of all the individual losses contributed by the channel filters and the combining network [7].

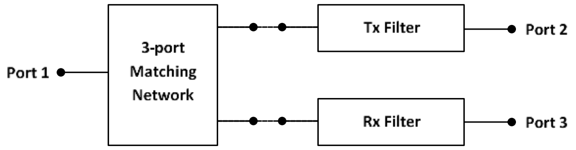


Fig.2. Diplexer architecture.

Different techniques have been investigated and reported for the design of diplexers. One interesting thing about the various methods is that different authors have reported different ways of matching and distributing energy between the Tx and the Rx channels of the reported diplexers. Some of the matching networks and energy distribution devices that have been reported include manifolds [8], circulators [9], T-junctions [10], Y-junctions [11], and common resonators [12]. Some authors have recently reported diplexers without external matching networks [13]. Various transmission line technologies, including planar and non-planar, have been employed in the implementation of diplexers. Some popular examples include waveguide [14], substrate integrated waveguide [15], coplanar waveguide [16], microstrip [17], and stripline [18].

The diplexer reported in this paper is based on a T-junction matching network and the microstrip transmission line for implementation. The originality and contribution of the work proposed here is that while the previously reported junction diplexers [10,12,19] rely on tuning and optimisation techniques to achieve matching at the junction, this paper proposes a novel formulation to make matching simple and reliable. This means that results can be easily reproduced by any researcher or design engineer worldwide by simply choosing their design specifications and utilising the proposed formulation. The proposed diplexer also exhibits very good isolation between the Tx and the Rx channels which is very encouraging.

II. CIRCUIT MODEL

The diplexer circuit model is formed from two separately designed channel filters and a T-junction as shown in Fig.3. The two channel filters are designed using the technique reported in [20], [21] with centre frequencies that correspond to those of the Tx and the Rx bands of the proposed diplexer. Each filter is designed to have a fractional bandwidth of 0.03; a passband return loss of 20 dB; and a characteristics impedance of 50 Ohms. Other design parameters of the channel filters are given in Table 1. From Fig.3, T1, T2, T3 and R1, R2, R3 are the resonators of the Tx and the Rx filters, respectively. TL_1 and TL_2 are the transmission lines for implementing the T-junction. The electrical lengths of TL_1 and TL_2 are 63 and 67 degrees, respectively.

The circuit model of Fig.3 was simulated using the Advanced Design System (ADS) circuit simulator, with the J-inverters modelled as pi-networks of capacitors as reported in [22]. The simulation results of the diplexer circuit model are presented in Fig.4 and show that the Tx and the Rx channels are centred at 2.6 GHz and 3.0 GHz, respectively; the isolation between the Tx and the Rx channels is better than 50 dB; the in-band return loss for both channels is greater than 20 dB; and the insertion loss is zero (i.e. ideal circuit condition).

Table 1: Channel filters design parameters.

Filter	**f_0, GHz**	**L, nH**	**C, pF**	**J_{01}**	**J_{02}**
Tx	2.6	0.1078	34.7529	0.02	0.0176
Rx	3.0	0.0934	30.1192	0.02	0.0176

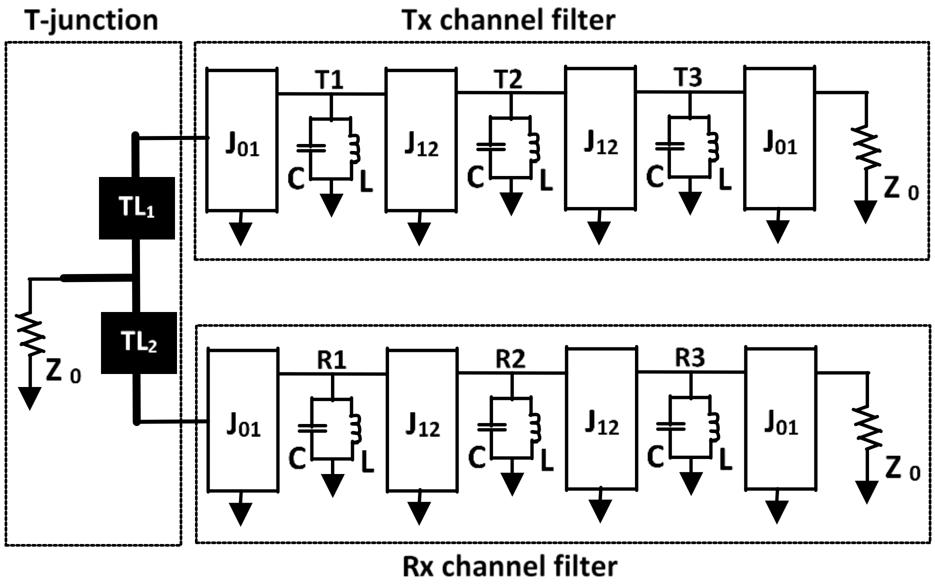


Fig.3. Diplexer circuit model showing identical LC resonators and J-inverters.

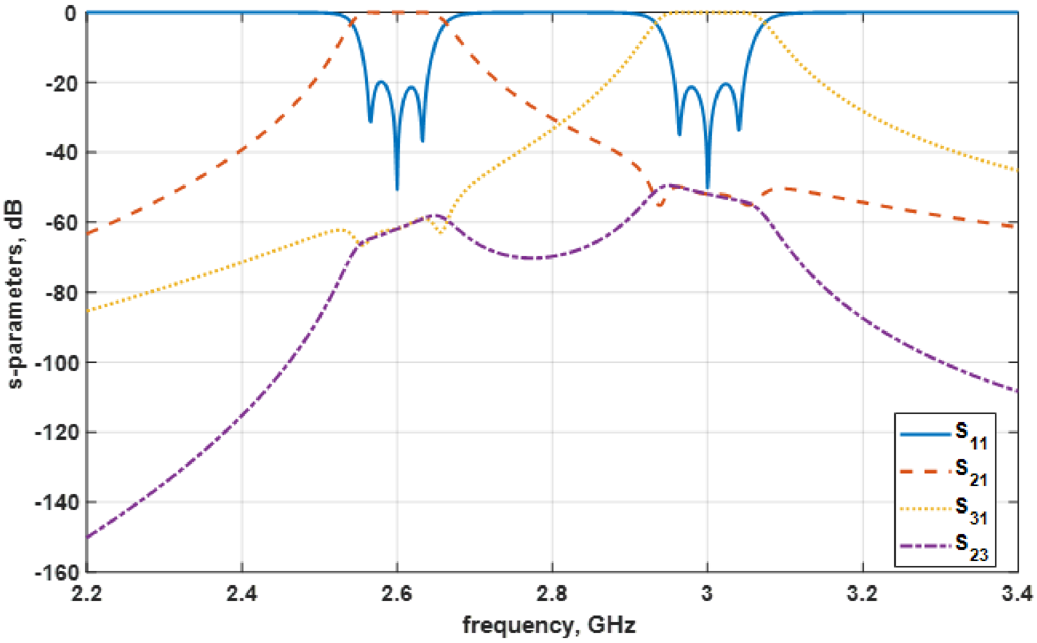


Fig.4. Simulation results of the diplexer circuit model.

III. MICROSTRIP LAYOUT

The microstrip layout implementation of the diplexer circuit is shown in Fig.5. The original idea behind the diplexer layout is based on the formulation used to design the T-junction section. The formulation is given in Equation (1), where EL is the electrical length of the given transmission line, λg is the guided-wavelength at one giga-Hertz frequency. The diplexer layout implementation is based on Rogers RT/Duroid 6010LM substrate with a relative dielectric constant $\varepsilon_r = 10.7$, a thickness $h = 1.27$ mm and a loss tangent $\tan \delta = 0.0023$.

The physical dimensions were determined using the ADS Momentum full-wave electromagnetic simulator. The Microstrip layout implementation results are presented in Fig.6 and show that the results closely match the circuit model results. However, an isolation of better than 42 dB is achieved when compared to the 50 dB isolation attained in the circuit model results of Fig.4. Unlike the circuit model design that is lossless, the microstrip layout implementation includes both conductor and dielectric losses. The loss tangent of the dielectric materials was kept at 0.0023, while the copper conductivity used for the simulation was maintained at 5.8 x 10^7 S/m, with a thickness of 35 micron for both the top and bottom metals of the microstrip line. Hence, an insertion loss of better than 1.1 dB is achieved, which is very encouraging.

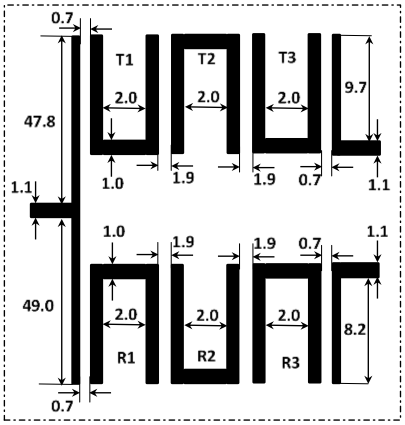


Fig.5. Microstrip layout of the diplexer circuit with all dimensions in mm.

$$\mathrm{TL}\ (\mathrm{mm}) = [(\mathrm{EL} + 90^{\circ})\ \lambda g]/360^{\circ} \qquad (1)$$

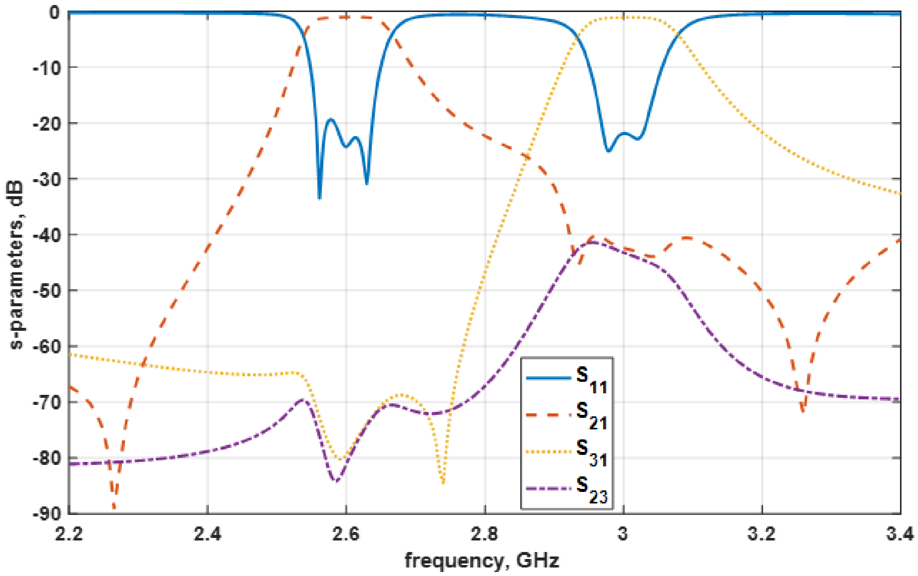
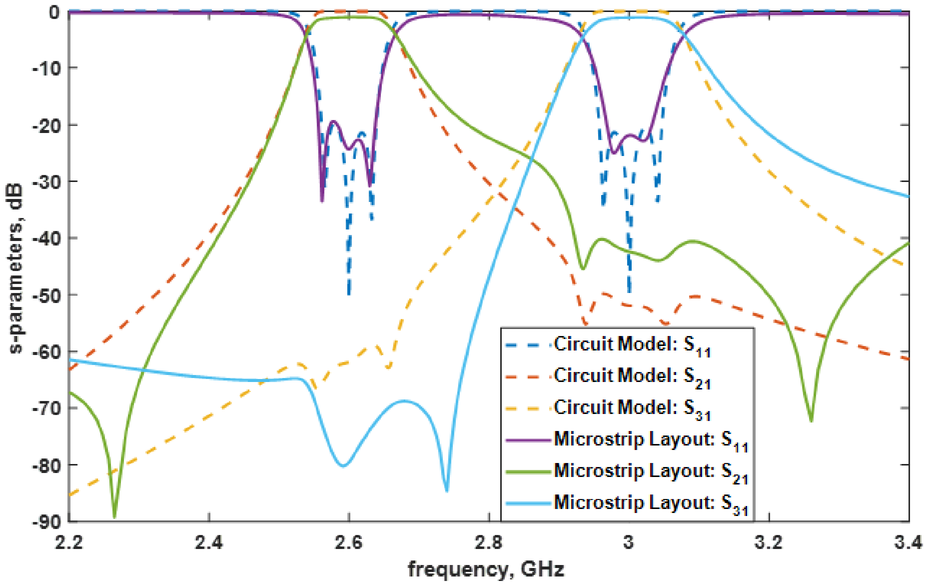


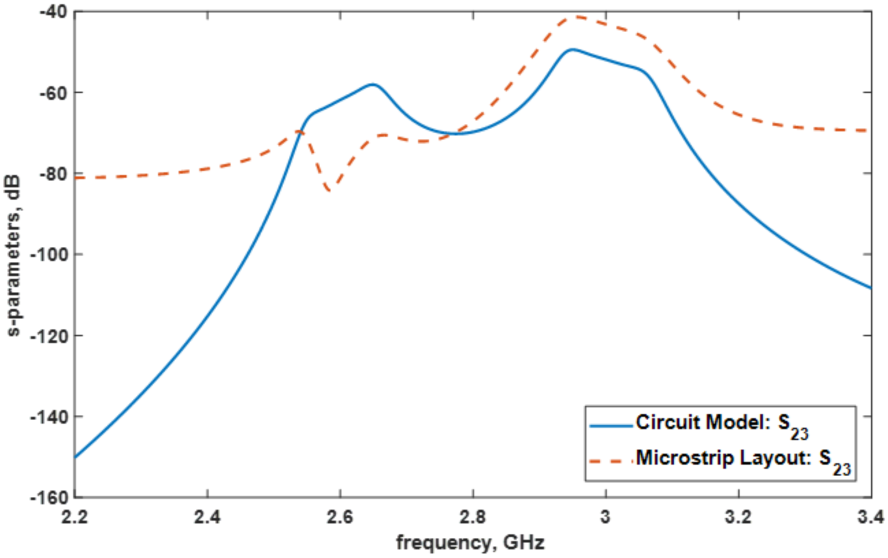
Fig.6. Microstrip layout results of the diplexer circuit.

IV. RESULTS COMPARISON

The diplexer circuit model and microstrip layout implementation results are co-presented in Fig.7 for easy comparison. The results show good agreement and proves that the design technique is not only simple but also reliable.



(a)



(b)

Fig.7. Results comparison. (a) Insertion and return losses. (b) Isolation between Tx and Rx.

V. CONCLUSION

A 6th order (6-pole) T-junction diplexer has been proposed, designed, and implemented using the microstrip transmission line technology. The circuit model and microstrip layout results show good agreement; with centre frequencies of 2.6 GHz at the Tx band and 3.0 GHz at the Rx band. A performance comparison with some published works [23]–[26] is presented in Table 2.

Table 2: Comparison between proposed diplexer and some recently published related works.

Ref.	f_1/f_2 **GHz**	**Iso.**[a] **dB**	**RL**[b] **dB**	**Selectivity**
[23]	1.8/2.4	>18.2	-	Low
[24]	2.45/2.98	>27.2	>15.3	Medium
[25]	1.0/1.15	-	>20.0	Low
[26]	1.73/2.25	>35.9	>15.0	Medium
This work	2.6/3.0	>41.6	>20.0	High

[a] Isolation, [b] return loss

ACKNOWLEDGMENT

The authors would like to thank Keysight Technologies for providing, at a nominal cost, the ADS software tool used for conducting all the simulations in this project.

REFERENCES

[1] A.O. Nwajana and K.S.K Yeo, *Practical approach to substrate integrated waveguide (SIW) diplexer: emerging research and opportunity*, 1^{st} ed., IGI Global, Hershey, PA, USA, 2020.

[2] A.O. Nwajana and K.S.K. Yeo, “Multi-coupled resonator microwave diplexer with high isolation”, *Proc. 46th European Microwave Conf.*, London, U.K., pp. 1167–1170, Oct. 2016.

[3] L. Zhu, R.R. Mansour and M. Yu, “A compact waveguide diplexer employing dual-band resonators”, *Proc. IEEE MTT-S International Microwave Symposium*, Tampa, U.S.A., pp. 1–4, Jun. 2014.

[4] Z.L. Wu, C.H. Lee and H.H. Chen, “Balun diplexer design in hybrid structure of microstrip line and slot-line”, *Proc. Asia-Pacific Microwave Conf.*, Nanjing, China, pp. 1–3, Dec. 2015.

[5] X. Guan, F. Yang, H. Liu, and L. Zhu, “Compact and high-isolation diplexer using dual-mode stub-loaded resonators”, *IEEE Microwave and Wireless*

Components Letters, Vol. 24, No. 6, pp. 385–387, Jun. 2014.

[6] H.L. Chan, C.H. Lee and C.I.G. Hsu, “Balanced dual-band diplexer design using microstrip and slot-line resonators”, *Proc. Asia-Pacific Microwave Conf.*, Nanjing, China, pp. 1–3, Dec. 2015.

[7] A. Nwajana, “Analysis and design of a substrate integrated waveguide multi-coupled resonator diplexer”, PhD Thesis, University of East London, London, U.K., Jul. 2017.

[8] Y. Heng, X. Guo, B. Cao, B. Wei, X. Zhang, G. Zhang and X. Song, “A narrowband superconducting quadruplexer with high isolation”, *IEEE Trans. Applied Superconductivity*, Vol. 24, No. 2, pp. 21–26, Apr. 2014.

[9] T. Kodera and C. Caloz, “Integrated leaky-wave antenna-duplexer/diplexer using CRLH uniform ferrite-loaded open waveguide”, *IEEE Trans. Microwave Antennas Propagation*, Vol. 58, No. 8, pp. 2508–2514, Aug. 2010.

[10] P. Zhao and K.-L. Wu, “Adaptive computer-aided tuning of coupled -resonator diplexers with wire T-junction”, *IEEE Trans. Microwave Theory Tech.*, Vol. 65, No. 10, pp. 3856–3865, Jun. 2017.

[11] K.L. Wu and W. Meng, “A direct synthesis approach for microwave filters with a complex load and its application to direct diplexer design”, *IEEE Trans. Microwave Theory and Tech.*, Vol. 55, No. 5, pp. 1010–1017, May 2007.

[12] T. Yang and G.M. Rebeiz, “Three-pole 1.3-2.4-GHz diplexer and 1.1-2.45-GHz dual-band filter with common resonator topology and flexible tuning capabilities”, *IEEE Trans. Microwave Theory and Tech.*, Vol. 61, No. 10, pp. 3613–3624, Oct. 2013.

[13] A.O. Nwajana and K.S.K. Yeo, “Microwave diplexer purely based on direct synchronous and asynchronous coupling”, *Radioengineering*, Vol. 25, No. 2, pp. 247–252, Jun. 2016.

[14] L.D. Palma, F. Bilotti, A. Toscano and L. Vegni, “Design of a waveguide diplexer based on connected bi-omega particles”, *IEEE Microwave and Wireless Components Letters*, Vol. 22, No. 3, pp. 126–128, Mar. 2012.

[15] A.O. Nwajana, A. Dainkeh and K.S.K. Yeo, “Substrate integrated waveguide (SIW) diplexer with novel input/output coupling and no separate junction”, *Progress In Electromagnetic Research M*, Vol. 67, pp. 75–84, Mar. 2018.

[16] C.-H. Lai, G.-T. Zhou and T.-G. Ma, “On-chip miniaturized diplexer using jointed dual-mode right-/left-handed synthesized coplanar waveguides on GIPD process”, *IEEE Microwave and Wireless Components Letters*, Vol. 24, No. 4, pp. 245–247, Apr. 2014.

[17] A. Rezaei, S.I. Yahya, L. Nouri and M.H. Jamaluddin, “Design of low-loss microstrip diplexer with a compact size based on coupled meandrous open-loop resonators”, *Analog Integrated Circuits and Signal Processing*, Vol. 102, Springer, pp. 579–584, 2020.

[18] W.-Q. Xu, M.H. Ho and C.G. Hsu, “UMTS diplexer design using dual-mode stripline ring resonators”, *Electronics Letters*, Vol. 43, No. 13, pp. 721–722, Jun. 2007.

[19] T.F. Skaik, M.J. Lancaster and F. Huang, “Synthesis of multiple output coupled resonator circuits using coupling matrix optimization”, *IET Microwaves, Antenna & Propagation*, Vol. 5, No. 9, pp. 1081–1088, Jun. 2011.

[20] A.O. Nwajana, K.S.K. Yeo and A. Dainkeh, “Low cost SIW Chebyshev bandpass filter with new input/output connection”, Proc. 16th Mediterranean Microwave Symposium, Abu Dhabi, U.A.E., pp. 1–4, Nov. 2016.

[21] A.O. Nwajana, R.I. Otuka, S.H. Ebenuwa, I.K. Ihianle, S.O. Aneke, and A. A. Edoh, “Symmetric 3dB filtering power divider with equal output power ratio for communication systems,” *2nd Int. Conf. on Electrical, Comm. & Comp. Engineering*, Istanbul, Turkey, pp. 1–4, Jun. 2020.

[22] J.-S. Hong, *Microstrip filters for RF/microwave applications*, 2nd ed., Wiley, New York, 2011.

[23] P. Deng, W. Lo, B. Chen, and C. Lin, “Designs of Diplexing Power Dividers,” *IEEE Access*, Vol. 6, pp. 3872–3881, Jan. 2018.

[24] G. Zhang, Z. Qian, and J. Yang, “Design of a compact microstrip power-divider diplexer with simple layout,” *Electronics Letters*, Nol. 54, No. 16, pp. 1007–1009, Aug. 2018.

[25] C. Chen, K. Zhou, R. Chen, Z. Wang, and Y. He, “Design of a microstrip diplexer-integrated filtering power divider,” *IEEE Access*, Vol. 7, pp. 106514–106520, Aug. 2019.

[26] C. Zhu, and J. Zhang, “Design of diplexer-integrated filtering power divider with high isolation,” *Microwave and Optical Technology Letters*, Vol. 61, No. 11, pp. 2607-2613, Mar. 2019.