A New Configuration Diplexer for RF Harvesting Applications

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Abstract. This paper presents an advanced microstrip diplexer specifically engineered for radio frequency (RF) energy harvesting. As key elements in multi-band harvesting setups, diplexers allow for the concurrent capture and conversion of ambient RF power across several frequency bands, leading to a substantial increase in the total harvested energy. The proposed design incorporates two band-pass filters, tuned to 5.8 GHz and 2.26 GHz, and constructed on a 1.6 mm thick FR-4 substrate (with a dielectric constant of 4.4 and a loss tangent of 0.025). A thorough evaluation of the filters' architecture and performance confirms their capability to convert ambient RF energy effectively. The diplexer efficiently segregates these frequency bands, enabling independent processing and rectification of the captured energy at each frequency. Such separation is essential for achieving maximum energy harvesting efficiency by reducing interference between bands and allowing the implementation of optimized rectifier circuits tailored to each band. Simulated S-parameters corroborate crucial performance indicators, including excellent impedance matching (low S11), minimal insertion loss (high S_{21} and S_{31}), and significant isolation between ports (low S_{23} and S_{32}), all of which are paramount for successful RF energy harvesting.

1 Introduction

The concept of radio frequency (RF) energy harvesting presents a promising and sustainable alternative to traditional batteries for powering low-power wireless devices [1, 2]. While ambient RF energy is readily available across numerous frequency bands (such as GSM, Wi-Fi, 3G, 4G) [3], its inherently low power density necessitates the development of highly efficient capture and conversion methodologies. To maximize the harvested power [4], employing multiband approaches is crucial, as these enable the simultaneous utilization of energy from various RF sources present in the environment. However, conventional multiband rectifiers, designed for concurrent operation across multiple frequencies, often encounter significant challenges. These include limitations in AC-DC conversion efficiency and difficulties in achieving consistent input impedance matching across a wide range of frequency bands [5, 6]. These issues stem from the inherent complexity of designing a single rectifier capable of operating efficiently and maintaining optimal impedance matching over such a broad spectrum. Consequently, performance trade-offs are often unavoidable, leading to less than ideal energy harvesting outcomes. To overcome these limitations, instead of relying on a single multiband rectifier, we propose the use of a diplexer to separate the 5.8 GHz and 2.26 GHz frequency bands. Each separated band is then directed to a specifically optimized rectifier designed for that particular frequency. This strategy offers several key advantages. Firstly, it simplifies the design and improves the efficiency of each individual rectifier, as each only needs to be matched at a single frequency. Secondly, it minimizes the potential for interference between bands, which can significantly reduce the overall energy harvesting efficiency. Thirdly, it allows for the implementation of specialized rectifier circuits that are precisely tailored to the unique characteristics of each frequency band, thereby further enhancing conversion efficiency. Maintaining adequate isolation between the two frequency bands is also essential to prevent signal leakage and preserve channel integrity [7, 8]. Furthermore, the physical realization of the diplexer, typically employing microstrip technology, requires careful attention to component dimensions and layout to minimize losses and ensure a compact design [9, 10]. The design presented in this work addresses these considerations, offering a viable solution for improved RF energy harvesting. This paper introduces a novel configuration for a dual-band RF energy harvesting system, with a particular focus on the design and implementation of the diplexer – a critical component that facilitates the efficient separation and processing of the 5.8 GHz and 2.26 GHz signals for subsequent rectification. The performance of this diplexer is paramount to the overall effectiveness of the system, as it directly impacts the amount of energy that can be harvested and converted [11, 12, 13, 14, 15]

2 Theoretical analyse of the bande passe filtre and diplexer

This section outlines the theoretical principles governing the operation of the proposed diplexer and its constituent filters, which are key elements for the efficient separation and conversion of RF signals.

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Filter Operation and Diplexer Function:
Microwave filters, including diplexers, operate based on transmission line and resonator theory. Even- and odd-mode analysis is employed to understand the behavior of the microstrip structure. The input impedance (Zin) of the microstrip structure is related to its characteristic impedance (Z_0) and reflection coefficient (Γ) according to the formula (1) $Zin = Z_0 \frac{1-\Gamma}{1+\Gamma}$ (1)
Where Γ, the reflection coefficient, is given by:

$$\Gamma = \frac{Zin-Z0}{Zin+Z0} \quad (2)$$

In a diplexer, impedance matching is crucial for minimizing losses and ensuring efficient frequency separation.
Frequency Response of a Coupled Resonator Filter:
The meandered structure forms a multi-resonator system, where each segment contributes to the overall frequency response. The resonant frequency of a microstrip transmission line resonator is given by the following formula (3):

$$fr = \frac{C}{2Leff\sqrt{\varepsilon effc}} \quad (3)$$

Where c represents the speed of light in a vacuum, Leff is the resonator's effective length, and εeff denotes the substrate's effective dielectric constant. Adjusting εeff allows for the selection of distinct frequency bands suitable for diplexing. The following section discusses. bandwidth and coupling coefficient. The bandwidth (BW) of the filter is influenced by the coupling coefficient (k) between adjacent resonators, expressed by formula (4): $k = \frac{f_2^2-f_1^2}{f_2^2+f_1^2}$ (4)
where f_1 and f_2 are the resonant frequencies of the coupled resonators. The spacing S between transmission lines controls k, impacting bandwidth and selectivity.
Insertion Loss and Quality Factor:
The insertion loss (IL) of the filter is linked to the loaded quality factor (QL), which is affected by dielectric and conductor losses as described by formula (5):

$$IL = 10log_{10}\ (1 + \frac{1}{QL}) \quad (5)$$

where QL is given by formula (6):

$$Q_L = \frac{f_r}{\Delta_f} \quad (6)$$

Where Δf represents the -3 dB bandwidth. A higher QL results in lower insertion loss and better filtering performance.
Application in RF Energy Harvesting:
The proposed diplexer is designed to separate RF signals from multiple frequency sources, such as Wi-Fi, GSM, and LTE. Each branch directs energy toward a rectifier circuit, where RF signals are converted into DC power. By optimizing parameters such as S, L, and W0 (spacing, length, and width, respectively), impedance matching and overall efficiency are enhanced, reducing losses and improving RF energy harvesting performance.
Mathematical Model of a Diplexer:
The operation of a diplexer can be characterized using S-parameters, which describe the transmission and reflection of RF signals between its ports. The scattering matrix (S) for an ideal, lossless diplexer is given by:

$$\begin{bmatrix} S11 & S12 & S13 \\ S21 & S22 & S23 \\ S31 & S32 & S33 \end{bmatrix}$$

For an ideal, lossless, and matched diplexer the S-parameters are defined by formula (7):

$$\begin{bmatrix} 0 & S12 & S13 \\ S21 & 0 & 0 \\ S31 & 0 & 0 \end{bmatrix} \quad (7)$$

S11 represents the reflection coefficient at the input port. S21 and S31 are the transmission coefficients from the input to the two output ports. The terms S12, S13, and S23 represent the coupling between the ports.
To ensure effective frequency separation, the isolation (ISO) between the two channels should be maximized, defined by formula (8):

$$ISO = -20log|S23|\ dB \quad (8)$$

For an optimal diplexer design, the insertion loss (IL) at each output should be minimized, given by formula (9):

$$IL = -20log|S21|\ dB$$
And $IL = -20log|S31|\ dB$ (9)

3 Design procedure and result discussion

3.1 Band-Pass Filter at 5.8 GHz

Simulations assessed the performance of the 5.8 GHz band-pass filter (layout in 'Fig. 1'). The resulting reflection coefficient (S_{11}, dashed red) and transmission coefficient (S_{12}, solid blue) are shown in 'Fig. 2'. The low S_{11} at 5.8 GHz indicates excellent impedance matching and efficient power transfer. The S_{12} plot shows near 0 dB transmission at 5.8 GHz, signifying minimal passband loss. The sharp S_{12} drop outside the passband confirms effective out-of-band attenuation. These simulations suggest a clear 5.8 GHz passband, good attenuation, and proper matching. However, a complete evaluation requires considering design specifications and other factors

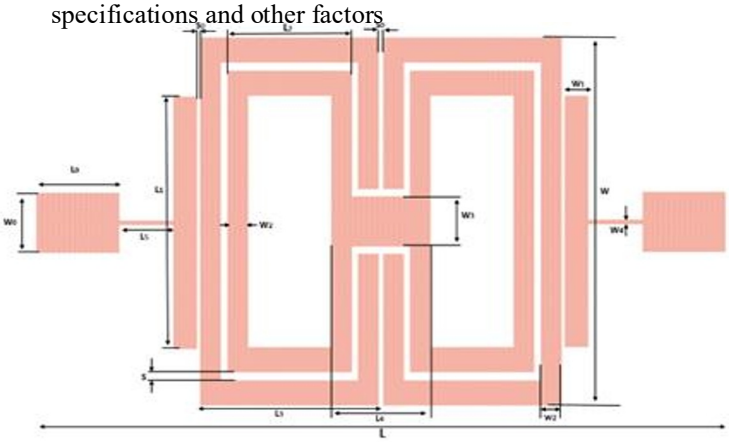

Fig 1. Layout of the Microstrip Band-Pass Filter Designed for 5.8 GHz RF Energy Harvesting Applications

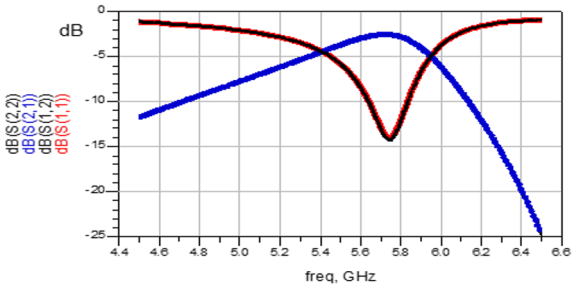

Fig 2. Frequency Response of the 5.8 GHz Band-Pass Filter: Transmission Coefficient S12 and Reflection Coefficient S11

3.2 Band-Pass Filter at 2.26 GHz

A compact meandered-line 2.26 GHz band-pass filter, suitable for space-constrained applications, is built using microstrip technology ('Fig. 3'). This filter employs stepped impedance resonators and open-circuited stubs for filtering. Its optimized layout balances size and performance for effective filtering at 2.26 GHz. 'Table 1' lists the filter's carefully optimized dimensions for peak performance at this frequency. The meandered transmission line structure is common in microwave filters like diplexers and band-pass filters. Parameters W and W_0 are the overall and transmission line widths, respectively. Spacing S affects capacitive coupling, while L and L_0-L_9 are lengths of transmission line sections acting as resonators and impedance transformers for frequency selectivity and performance.

Table 1: Dimensions of the Proposed Filter

Parameters	mm
W	19.65
W_0	1
S	0.4
L	28.35
L_0	5
L_1	17.29
L_2	6.86
L_3	4.86
L_4	17.92
L_5	6.14
L_6	W
L_7	4.14
L_8	2.54
L_9	18.36

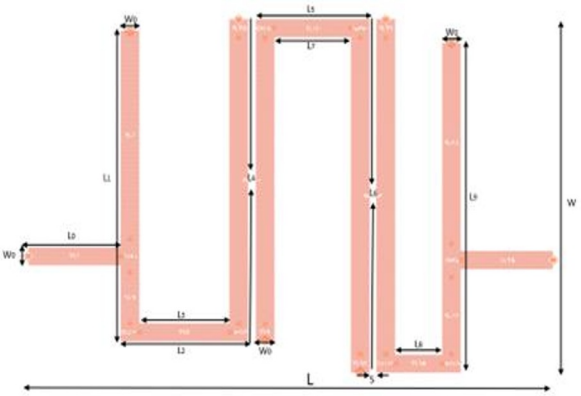

fig.3 Compact Meandered-Line Bandpass Filter for 2.26 GHz Applications

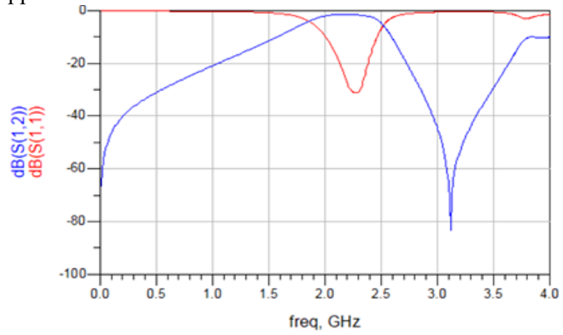

Fig. 4: Simulated Performance of a Compact Meandered-Line Bandpass Filter at 2.26 GHz

The 'Fig. 4' shows the simulated frequency response of this compact 2.26 GHz meandered-line band-pass filter, displaying transmission (S_{12}, blue) and reflection (S_{11}, red) coefficients. Simulations confirm a well-defined 2.26 GHz passband with low insertion loss and satisfactory return loss, demonstrating excellent selectivity in isolating this band. These results validate the design's effectiveness.

3.3 Connecting the Two Band-Pass Filters

'Fig. 5' illustrates the microstrip diplexer structure used to combine the 2.26 GHz and 5.8 GHz band-pass filters for effective frequency separation and signal routing. The design features a T-junction with optimized impedance-matching transmission lines to minimize interference and insertion loss, ensuring efficient frequency discrimination and low return loss for simultaneous filter operation without performance degradation. Key elements for frequency separation and signal routing are the optimized transmission lines (TL1, TL2, TL3) and the T-junction.

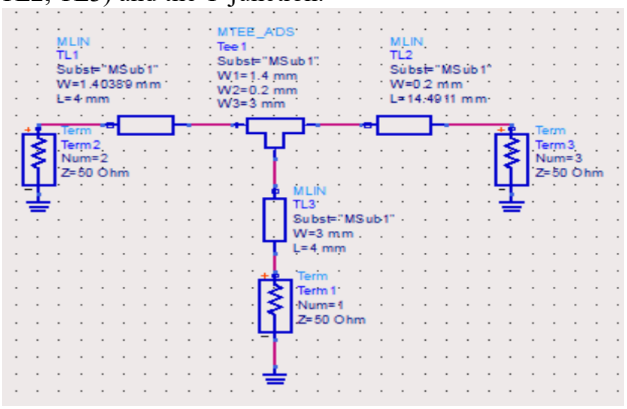

Fig.5 Diplexer Structure for Integrating 2.26 GHz and 5.8 GHz Band-Pass Filters

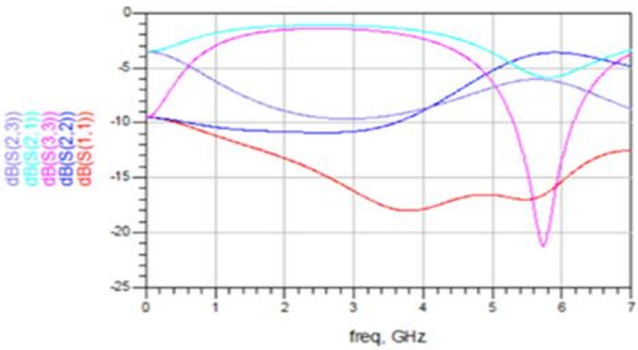

Fig.6 Simulated S-Parameters of the Microstrip Diplexer

'Fig. 6' shows the simulated S-parameters of the microstrip diplexer (generated in ADS), confirming effective frequency separation between the 2.26 GHz and 5.8 GHz channels. The S11 (red line) indicates good impedance matching (return loss < -10 dB) at both frequencies. Transmission coefficients S21 (blue) and S31 (purple) show efficient signal routing with minimal insertion loss. High isolation between output ports is observed (low S_{23}/S_{32}, light blue/pink). These simulations validate the proposed diplexer's effectiveness for RF energy harvesting by integrating the two band-pass filters ('Fig. 5') with a common input and two separate outputs via optimized microstrip lines.

3.4 Diplexer Design and Implementation

Diplexers are essential for RF energy harvesting by selectively routing or combining signals at different frequency bands using two band-pass filters directing signals to distinct output ports based on frequency. They are crucial in wireless communication, antenna multiplexing, and RF energy harvesting for optimizing performance and minimizing interference through effective frequency management.

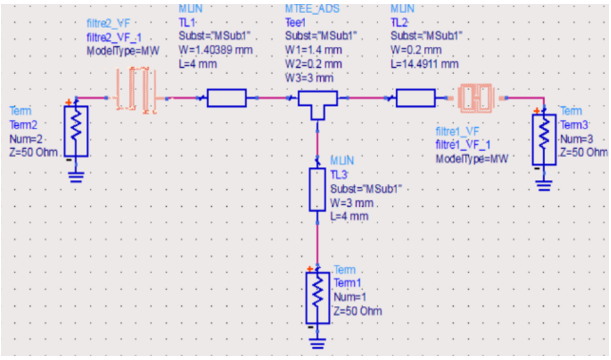

Fig.7: Schematic of the Proposed Microstrip Diplexer

The proposed diplexer was designed and simulated using Advanced Design System (ADS). The schematic, depicted in 'Fig. 7', illustrates the integration of two band-pass filters with a T-junction configuration. This configuration merges the filters at a common input port and separates them at two distinct output ports. The design ensures impedance matching and minimal cross-talk between the two frequency channels, crucial for efficient and isolated signal routing.The optimized microstrip transmission lines and the T-junction are key elements in achieving the desired frequency separation and signal routing.

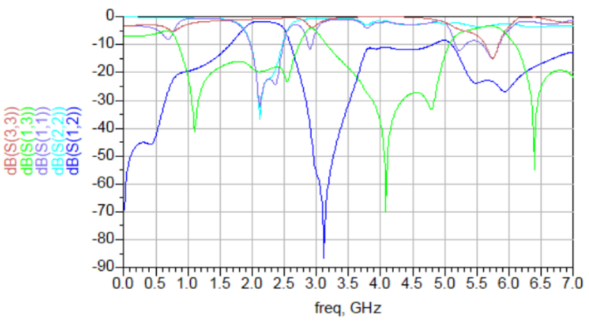

Fig.8: Simulated S-Parameters of the Microstrip Diplexer Demonstrating Frequency Separation at 2.26 GHz and 5.8 GHz

'Fig. 8' presents simulated S-parameters validating the diplexer's efficient signal routing at 5.8 GHz and 2.26 GHz. Key characteristics include: good impedance matching (S_{11} below acceptable limits at both frequencies), low insertion loss (minimal loss in S_{21} and S_{31} for efficient transmission), and high isolation (low S_{23} and S_{32} effectively preventing interference). These results confirm the proposed diplexer's effectiveness for RF energy harvesting by separating signals at different bands with minimal losses, crucial for efficient energy harvesting from multiple RF sources.

4 Conclusion

The article presents a compact and efficient microstrip diplexer design for dual-band RF energy harvesting. The optimized design, incorporating two band-pass filters and a T-junction configuration, achieves effective frequency separation, low insertion loss, and high isolation. The simulated results validate the proposed diplexer's performance and its potential for enhancing the efficiency of RF energy harvesting systems by enabling the simultaneous capture and processing of energy from multiple frequency bands. This work contributes to the advancement of sustainable energy solutions for low-power electronic devices.

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