# Miniaturization Processes of Transmission Lines with Respect to Metamaterials, Energy Efficiency, and Operating Frequencies

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**ABSTRACT**

*Miniaturization techniques regarding the design of transmission lines are reviewed based on metamaterials, energy efficiency, and operating frequency. It shrinks circuits and line spaces strategically without compromising performance. It supports techniques that are aimed at improving the space and performance. The metamaterials are synthetized structured materials that have unique and unusual properties (such as photonic crystals, plasmonic, etc.) thereby possessing important manipulative properties that can be utilized in the design of antennas, filters, lenses, sensors, controllers, and so on. Miniaturization supports efficient use of energy among components through several computational and mechanical techniques like minimizing number of components, material loading, shorting and folding, ground-plane modification, slotting, metamaterials, and so on. In the mechanical systems, miniaturization depends on maintaining or improving response of operating frequency by considering several efforts to reduce size of systems. Miniaturization technology reduces the size of circuits and lines thereby enhancing performance.*

**KEYWORDS**

*Miniaturization, transmission lines, met materials, energy efficiency, operating frequencies*

## I. INTRODUCTION

Miniaturization refers to a process reducing the size of a component to using advanced techniques. Several integrated circuits have now been reduced to small-sized. For example, semiconductors like silicon chips are becoming smaller because of miniaturization. Designs that used met materials utilize miniaturization as a key technological innovation. To achieve smaller-sized devices, it is possible that electromagnetic properties of traditional materials are manipulated at sub- wavelength scale [42]. For example, a lens made with a met material could be as small as a few microns, whereas a conventional lens would need to be much larger to achieve the same functionality. In addition, miniaturization of electronic components for higher frequencies where there is a constant effort to make electronic components, such as transistors and capacitors, smaller in size. This miniaturization allows for higher operating frequencies in electronic devices. In the context of electronics, higher frequencies often translate to faster data processing and communication. Other than that, in the field of wireless communication, there's a continual push for miniaturization of devices and components. This can lead to the development of smaller and more efficient antennas, transceivers, and other components, enabling the use of higher frequency bands for communication. Miniaturization is important for several applications, including consumer electronics, medical devices, and sensors. It can also lead to reduced power consumption and weight savings.

## II. MINIATURIZATION

Recent articles and practices are investigated and discussed in this work. It is done by summarizing technologies regarding miniaturizing transmission lines to support sustainable transmission of resources such as power and data. Industrial practices and regulatory recommendations are also considered in the work. This work is qualitative type of research. It investigates and discusses recent technologies regarding miniaturizing transmission lines in terms of materials, energy efficiency, and operating frequencies of lines. Miniaturizing transmission lines reduces material spacing, improves performance, energy efficiency, offer ranges of operating frequencies, and so on. Recent miniaturization technologies that enhance transmission are discussed based on three key areas: met materials, energy efficiency, and frequency.

### *A. Miniaturization for Met materials*

Met material is a macroscopic composite, where the material is engineered to have the ability that is not exist naturally [31] Despite their absence in nature, these materials have been theoretically validated for their ability to manipulate the behaviour of electromagnetic waves, showcasing phenomena such as the reversal of Snell's Law, Doppler Effects, and Cherenkov radiation [32]. The different size and the geometry shape of this material will provide a different ability to it. These properties are dependent on the geometric structure and arrangement of the materials within the met material. Among the features, met material can manipulate material to have negative permittivity (ε- negative), negative Permeability (μ-negative), single-negative (SNG) and Double-Negative (DNG) [34]. Negative permittivity signifies an electric displacement field opposing the applied electric field, while negative permeability implies a magnetic induction field in the opposite direction. Single-Negative (SNG) characteristics pertain to either the electric permittivity or magnetic permeability being negative, while Double-Negative (DNG) occurs when both possess negative values. Split Ring Resonator and Complementary Split Ring Resonators have been used extensively in reducing the size on the microwave transmission lines for various application such as antenna balun, filter, resonator, and so forth [45]. Split ring resonator consists of two concentric rings with a split in each ring creating a small gap.

Resonators suggest the behaviour of the structure in exhibiting certain magnetic resonance at certain frequency. A comparison study between a common patch antenna designed using an FR-4 substrate with a dielectric constant of 4.4 and the same patch antenna designed using a met material. Has shown a reduction in antenna size by a factor of 2.4 and towards an increased gain from 4.17 dBi in the conventional design approach to 5.66 dBi in the met material design [33]. Two metallic star-shaped split-ring resonators for antenna design for 6G terahertz wireless application. The designed provides negative permittivity and near-zero permeability, and a negative refractive index at its operating frequency of 0.25-0.32 THz and 0.391-0.396 THz. The slotted-strip line has been used to split the resonator patch at the centre to have the frequency tuning capability. The proposed design has a size of 160 μm x 52 μm, which is smaller than some of the other reported state-of-the-art met material designs for terahertz wireless applications [34]. Ten identical SRR structures that being placed in symmetrical pattern to design the radiating patch of the 5G antenna. The designed managed to reduce the size on the antenna by 22.2 % from 40 x 45 mm to 35 x 40 mm while maintaining the directivity and maximum gain [35]. A proposed multi-layered 5G antenna design with a layer of Split Ring Resonator (SRR) has been placed between the top and the ground plane [36]. The position of SRR in such a way to act as a precise mirror that avoids introducing phase variations in the reflected electromagnetic waves. This action leads to an enhancement of the radiation characteristics of the ground plane located beneath the antenna. The authors also fabricated the antenna using a three-layer 3D-inkjet printing process on a flexible and biocompatible substrate called polyethylene naphtha late (PEN). The fabrication process involves the use of specialized 3D printer, which employs material jetting to apply conductive ink. The fabrication steps include printing the patch, automated alignment for SRR printing, and printing the ground plane. The resulting prototype is a flexible and bendable miniature antenna. An antenna is designed with square tooth-based split ring resonator. The square tooth-based said to provide multiband operation which allow for wide range of frequency coverage, providing higher gain and bandwidth [37]. Combinations of SRR and CSRR pattern in antenna design were presented. With the application of SRR, the size of the cell manages to be reduced by 22 %. Further, with the introduction of CSRR into the design, it shows a better impedance matching [38]. A rectangular patch micro strip antenna miniaturization by using complementary split ring resonator (CSRR) structure for 3G mobile communication system on 2.1 GHz.

The structure is implemented on the micro strip ground plane. Simulation evaluation by using the AWR simulator shows that the CSRR structure is able to reduce antenna dimension about 62.71 % from 3192 mm2 (56 mm × 57 mm) to 1190 mm2 (34 mm × 35 mm). Beside miniaturization, VSWR and return loss also experience improvements about 1.05 and -33.83 dB subsequently. Bandwidth increment about 70.37% is also achieved [39]. A proposal is made on adopting locally resonant met material (LRM) in designing a Ka-band filters. LRM is a type of met material that leverages local resonances to achieve unique electromagnetic responses. The filter implements sub wavelength guiding mechanism in an evanescent rectangular waveguide, loaded by ultra-small pins, forming a composite pin-pipe waveguide (CPPW). In this study also, the authors implement a unique sub wavelength method called meta-port to improve the impedance matching with the standard WR28 interfaces that being used. This design proves to have the capability of customizable bandwidth, low insertion loss and high rejection level for 6th and 7th order. The total length also less than the operating wavelength and significantly lighter than traditional [40]. A work presents a two-pole band pass filter which designed for cellular applications by implementing composite right- and left-handed transmission line (CRLH-TL) approach. The CRLH-TL are a class of met material transmission lines that exhibit both right-handed (RH) and left-handed (LH) characteristics simultaneously within the same structure. The RH and LH regions are determined based on the dispersion diagram, which is a plot of the phase constant (β) versus the angular frequency (ω) of the electromagnetic waves propagating through the filter. In the dispersion diagram, the RH region is observed where β is greater than 0, and the LH region is observed where β is less than 0 The designed filter utilizes 2-ohm shaped inter digital capacitor (IDC) to generate two poles at 2.23 GHz and 2.35 GHz for better impedance matching. The size filter designed is 8.8 mm × 11.2 mm [41]. A compact met material unit-cells is design of based on the stepped- impedance resonator (SIR) technique to further reduce and improve the designer of conventional CSRR on substrate integrated waveguide (SIW) filters. The proposed SIR-CSRR unit-cells have larger electrical size compared to conventional CSRR. Three types of designed has been proposed with different configuration. The size of conventional SIW-CSRR is 0.261λ × 0.127 λ while the total size of the proposed SIW filters 0.158 λ × 0.077 λ [42]. A work presents a dual-band (DB) half-mode substrate integrated waveguide (HMSIW) filters by implementing met material unit cell with double negative permittivity. This unit cell allows for the independent tuning of the centre frequencies of the pass bands by altering the dimensions of the DB met material unit cell. The proposed filter designed to operate at centre frequencies of 2.4 GHz and 3.5 GHz for WiMAX applications. The designed achieved size reduction with total size of less than 0.10 λ × 0.10 λ for the proposed two-stage DB HMSIW filter [43].

A compact Marchland balun configuration employing a pair of quarter-wave edge-coupled transmission lines and two-unit cells of complementary split-ring resonators (CSRR) embedded in the ground plane. These coupled lines are connected through an uncoupled micro strip line, with short circuit and open circuit terminations assigned to specified ports. The integration of two rectangular CSRR cells contributes to the improvement of circuit performance. To broaden the bandwidth, a step impedance technique has been implemented at the balanced ports. The proposed design achieves a fractional bandwidth of 18.75% at the central frequency. The overall circuit size is 30.72 mm × 16.63 mm [[44]. Integration of CSRR pattern into a substrate-integrated waveguide (SIW) filter to reduce the size of the filter. The CSRR structures were surface etched on to the micro strip. To enhance the interaction or improve the coupling between adjacent CSRRs, the middle metal strip is also etched away. By doing this, the transverse electric mode (TE10) field distribution will be compressed, leading to more concentrated and stronger coupling between CSRR structures. The overall design of the filter is cantered on a frequency of 22.6 GHz. Authors also introduced multiple transmission zeros (TZs) to enhance the filter’s skirt selectivity, allowing for more precise and selective filtering behaviour [45]. Another integration of CSRR pattern into half-mode substrate integrated waveguide (HMSIW) resonators to reduce the dimensions of the HMSIW devices. Table 1 below show summary on the impact of met materials in the miniaturization process.

Table 1: Summary of miniaturization based on met materials

| Application | Frequency | Design | Features |
|---|---|---|---|
| Antenna | 2.4 GHz | Met material. | Reduced-size and increased gain by 1.5 dB. |
| Antenna | 0.25 – 0.32 THz 0.39 – 0.40 THz | Star-shaped Split-Ring-Resonator (SRR). | 160 × 52 μm |
| Antenna | 3.5 GHz | Identical and Symmetrical SRR. | Size reduction by 22.2% to 35 × 40 mm |
| Antenna | 3.5 GHz | SRR layer between top and the ground plane. | Small, flexible, and bendable miniature. |

| | | | |
|---|---|---|---|
| Antenna | 3 – 9 GHz | Square tooth based SRR. | 66.4 × 66.4 mm wide range of frequency, high gain, and bandwidth. |
| Antenna | 2.1 GHz | Complementary split-ring resonators (CSRR) on ground plane. | Reduction of size by 62.71% |
| Antenna | 3.3 GHz | Combining SRR and CSRR. | Size reduction by 22% |
| Ka-band filter | Ka band | Locally-resonant-met material (LRM). | Reduced-size filter. |
| Band pass filter | 2.23 – 2.35 GHz | Composite right- and left-handed transmission-line (CRLH-TL). | 8.8 × 11.2 mm |
| Substrate-Integrated Waveguide (SIW) filter | | Stepped-impedance resonator (SIR) and Complementary split-ring resonators (CSRR). | Size reduction compared to conventional CSRR. (0.158 × 0.077 λ). |
| Half-Mode Substrate Integrated Waveguide (HMSIW) filter | 2.4 – 3.5 GHz | Unit cell with double negative permittivity. | 0.10 × 0.10 λ |
| Substrate-Integrated Waveguide (SIW) filter | 22.6 GHz | Complementary Split-Ring Resonators (CSRR). | Size reduction. |

*B. Miniaturization for Energy Efficiency*

Energy faces challenges on its usage, reliability, security, stability, and availability for power systems and transmission lines. Miniaturization is a promising technology that reduce circuit space without compromising performance. It involves strategies that promote effective energy management within components. The energy efficiency is an important consideration while designing components using miniaturization techniques. It has significant impact on operational and capital expenses, and environment. Miniaturization reduces components to small-sized, and it is optimum to achieve high efficiency on power along circuits and transmission lines. Achieving high energy efficiency involves optimum operational strategies on the usage of energy. The growing demand on energy makes industries to deploy techniques that balance energy input and output. Emerging semiconductor technologies support effective energy management and miniaturization of components [1]. Met materials used for miniaturization; create materials with suitable properties from internal structure [3]. Miniaturization reduces circuit and line spaces so also to improve performance. Trade-offs do occur between the size and efficiency; as in the case of travelling-wave-direct-energy-converter used in spacecraft for energy recovery [4]. Electronic industries are utilizing techniques to create smaller-sized and high-performing components. Micro strip-patch-antenna (MPA) realize the impact of miniaturization under some techniques; loading, reshaping, shorting and folding, ground-plane, slotting, met materials [5]. For the MPA, the trade-off is between bandwidth and size. Small-sized antenna ensures seamless components' integration. Adjusting conducting layers in a design provide strong capacitive-coupling and achieve over 70% improvement [6]. The 800 V Thermistor (power control module) introduced by STMicroelectronics operates in high temperature environment without dating [7]. Artificial intelligence can be utilized to support design innovations regarding energy management under miniaturization [8]. Miniaturization is a continual process of shrinking microelectronic devices and lines by deploying advance scientific innovation to create smaller and more powerful devices. Power supply miniaturization can be achieved through minimizing number of external components (inductor, capacitors, and resistors) through integration [23].

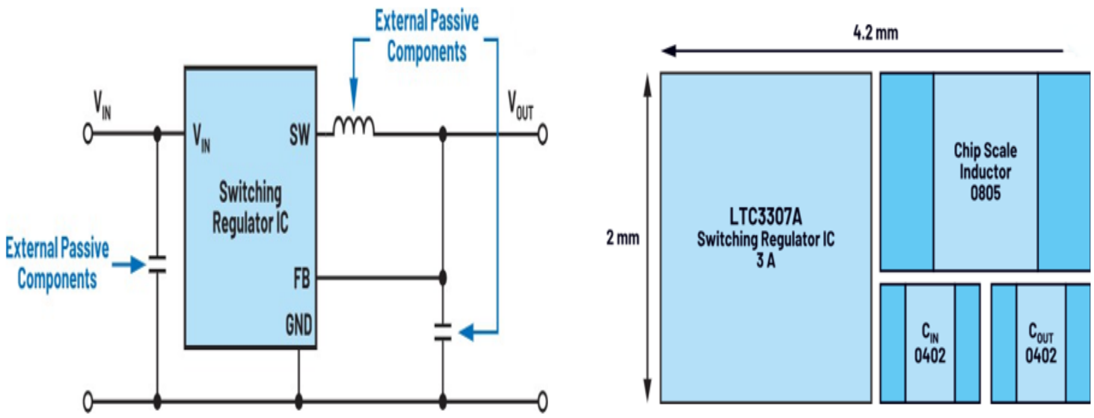


Figure 1: Minimized components for Switch-mode Buck Converter [48]

The Moore's law establishes a steady pace of computational progress which results in the generation of smarter, faster, and smaller electronic devices. Smaller, faster chips provide more options to boost product performance. But their development requires new levels of cross- disciplinary problem-solving to meet demands for more powerful components and products in ever-shrinking form factors [2]. In 2021 the IBM unveiled 2-nm chip technology which allows the placing of 50 billion transistors onto a space about the size of a fingernail. The technology supports 75% lower energy use than the 7-nm node chips technology. Achieving high-performance and high-efficiency across components and products, designers utilize cross-disciplinary innovations to prolong cycle-life, reduces carbon footprints, accelerates functions, increases speed, high frequency, low power consumption, low latency, and so on. The cross-disciplinary innovation benefits the electronic industries. The 5G network is miniaturization-hungry technology that requires shrinking of components to provide high performance and flexibility. Cross-disciplinary design enhances the conventional design with more innovative and collaborative approaches to address issues such as; size, efficiency, bandwidth, attenuation, interference, etc. It creates new components with improved functionality. A high-performing broadband miniaturized transmission waveguide is achieved using complementary spoof surface Plasmon polaritons [11]. It consists of a corrugated slot line and a group of additional interdigital structures which determined the degree of miniaturization. Components such as rectenna; are reduced to occupied small space in wireless power transmission with comparable performance. A special miniaturized rectenna of compact design and symmetric CPW-fed is designed and used for wireless energy harvesting [13]. Portable wireless electronic devices (internet-of-things (IoT) devices) like sensors and controllers are mostly battery-operated with limited lifetimes [14], alternative sources of power are required to maintain functionality such as using the available RF in the ambience to harvest certain amount of energy. Miniaturization support better portability and performance. The Micro Photosynthetic Power Cells (μPSCs) paves way for bioelectricity generation technology to meet low-power application using photosynthetic capabilities [15]. It boosts power density and enhances performance. Dynamic line rating (DLR) is a miniaturization technology that optimize power usage along power density [16]. It uses sensors to capture real-time electrical data to analyse transmission conditions of transmission for decision. Miniaturized rectennas are used in medical applications for energy conversion [17]. They are mainly used to convert AC-to-DC voltage for usage in low-power electronics devices such as implantable medical devices (IMDs). Miniaturization is involved in the design of printed circuit board (PCB) of reduced physical dimensions [18]. The design of small-scaled generators to support high performance at low frequencies is a new metric [19].

High efficiency is found in single-degree-of-freedom resonators. A promising conversion strategy in power control is the use of two-stage ac-dc converters for grid- connected power control [20]. The process improves power efficiency to meet specifications. Miniaturization has an impact on space and energy efficiencies for wireless sensor networks (WSNs) application. The WSNs collect and send operational data for decision-making. WSN is power-hungry; hence, the need for backup. The cavity resonance-enabled-wireless-power-transfer (CR-WPT) is designed to obtain optimum efficiencies [21] along transmission line. Miniaturized wide-pass-band filter is designed using composite of right/left- handed transmission line to provide efficient broadband filtering [25]. Miniaturizing microwave planar circuits using composite micro strip/coplanar waveguide transmission lines enhance performance [30]. Circuits of power dividers and filters in amplifiers and antenna feed-networks occupying large-size circuit boards can be miniaturized to achieve high performance by consolidating micro strip lines and coplanar waveguide lines on a single dielectric substrate. Small-sized wireless transmission antenna is designed using artificial transmission line loading [28]. Such antennas have compacted radiating element supported by ground plane structure and fed by a line transition structure. Table 2 below, provides summary of applications for miniaturizing transmission line with respect to energy efficiency.

Table 2: Summary of miniaturization of transmission lines based on energy efficiency.

| Application | Function | Material/Design |
|---|---|---|
| Wireless Communication (Micro strip-patch-antenna, Bluetooth) | Energy saving | Met materials |
| Wireless Power Transfer (Rectenna) | Energy conversion | Low-cost materials |

| | | |
|---|---|---|
| IoT applications<br>(Sensors, Controllers) | Energy conversion | Low-cost materials |
| Broadband Transmission Waveguide<br>(Plasmatic Integrated Circuits) | High performance | Inter-digital structures |
| Medical application<br>(Rectenna) | Energy conversion | Antenna and rectifier |
| Aviation and Spacecraft | Energy recovery | Low-cost (Si, GaAs),<br>and piezoelectric (PZT) |
| Power Control<br>(800-V Thyristor) | Energy efficiency | Low-sized materials |
| Artificial Intelligence | Power management | Computational materials |
| Devices<br>(Computer, Phones, etc.) | Energy integrity | Low-sized and<br>Shrinking components |
| Wireless Sensor Networks | Optimize energy and<br>grid control | Computational and<br>Mechanical materials |
| Conversion and other designs<br>(Switch and 2-stage converters) | Improve energy | Active and passive Components. |
| Filter and other Microwave Circuits<br>(WBPF, Antenna, etc.) | Broadband filtering, and artificial transmission | Low-sized materials |

*C. Miniaturization of Transmission Lines based on Operating Frequencies*

Miniaturization on transmission line for frequency can be in wide variety range of area and trend. Main purpose to determine whether the frequency is really give huge impact in transmission line. One of the purposes is to reduce the size of transmission lines while maintaining or optimizing their performance at specific frequencies. Efforts in these areas typically involve advanced materials, innovative design techniques, and a deep understanding of electromagnetic principles to achieve the desired miniaturization without compromising performance. Researchers and engineers often employ techniques like met materials, planar transmission lines, and advanced fabrication processes to achieve miniaturization in the transmission lines for specific frequency bands. In this section, few research paper from different author on related miniaturization in frequency of various type of aspect and context is discussed.

In wireless communication systems, especially those involving small electronic devices like smartphones or IoT devices, there's a need for miniaturized antennas and transmission lines. This enables the integration of communication components into compact devices while still operating efficiently at specific frequencies. Focus involving the miniaturization of circular resonators in waveguides at Super High Frequency (SHF) using floral foam within the realm of electromagnetic engineering with effort to reduce the size of circular resonators, which are components that exhibit resonant behaviour at specific frequencies. Super High Frequency (SHF) refers to the frequency range between 3 GHz and 30 GHz which is it is common frequency range for various communication and radar applications. Another unique approach is Floral Foam in Electromagnetic Engineering as a substrate or component within the resonator or waveguide structure. Research in this area might involve designing resonators that efficiently operate within the SHF range, considering the dielectric properties of floral foam, and assessing how this material affects the overall performance of the waveguide and resonator system [51]. A proposed work on reducing the size of a circular ring slot patch antenna while maintaining its functionality, particularly for low-frequency applications. This circular ring slot patch antenna, in this case, has a circular ring or slot incorporated into its design, which can affect its performance and characteristics to pursue to meet space constraints or design requirements. Antennas designed for low frequencies may be used in various applications such as communication, RFID systems, or sensing. Achieving miniaturization in antenna design can involve various techniques, including optimizing the shape and dimensions of the radiating elements, using advanced materials, or incorporating met material structures. Besides, other researchers need to explore new strategies to reduce the overall size of the antenna without sacrificing its performance characteristics. This could involve adjusting the dimensions of the circular ring, optimizing the feed structure, or employing techniques like fractal geometry [52]. A novel design for a miniaturized dual frequency RFID antenna capable of operating in both the HF (13.56 MHz) and UHF (860-960 MHz) bands. The antenna design aims to achieve a high frequency ratio, around 70, to support RFID applications.

The design involves relocating the UHF electric dipole antenna inside the HF coil antenna to reduce overall size, while maintaining reasonable impedance match. The miniaturization is achieved through modifications to the HF coil and UHF dipole, resulting in a smaller antenna with almost the same performance as the previous design. The frequency ratio of the dual frequency antenna in this paper, which is around 70, is notably higher than the frequency ratios typically found in common dual frequency antennas. The paper mentions that dual frequency antennas with a frequency ratio within 1.8 - 4.9 are common. This indicates that the frequency ratio of the antenna presented in the paper is significantly higher than what is typically observed in other dual frequency antennas. This high frequency ratio is a distinctive feature of the antenna design presented in the paper and is tailored to support RFID applications operating in both HF and UHF bands [53]. The design modifications, including the relocation of the UHF electric dipole antenna inside the HF coil antenna, result in a smaller antenna with almost the same performance as the previous design. A work proposes the use of nested composite rings suggests a sophisticated approach to achieve desired performance characteristics, such as impedance matching, radiation pattern control, and possibly polarization diversity. The design could involve careful tuning of the dimensions of the rings and the micro strip elements to meet the requirements of the Beidou system. Nested Composite Ring Micro strip Antenna is where multiple rings are arranged in a nested or layered configuration. The

Arrangement could be concentric circles or have a different geometric layout. Multi-frequency antennas are valuable in systems that need to communicate or receive signals across different frequency bands. Appears that the antenna design is intended for use in the Beidou Navigation System, and it incorporates nested composite ring structures on a micro strip substrate to achieve multi-frequency operation. Such an antenna might be designed to cover specific frequency bands associated with the Beidou system, ensuring reliable and accurate communication with the satellite network [54].

Frequency selective surfaces are characterized by small size, stability under varying incident angles, and the ability to operate in two distinct frequency bands within the terahertz regime. This type of design could find applications in advanced communication systems, terahertz imaging devices, or other technologies where precise control over electromagnetic waves in the terahertz frequency range is required. The challenge in the terahertz regime often lies in achieving compact designs and stable performance across various angles of incidence [55]. Miniaturization in transmission lines can also refer to the design of transmission lines on a PCB. For high-frequency applications, such as in RF circuits, the layout and design of transmission lines on the PCB need to be carefully optimized to minimize signal loss and interference while occupying a small footprint. A specialized electromagnetic structure '2.5-D' is described where the 2.5–D aspect suggests that it has some level of three-dimensional features, and its "miniaturized" to fit specific size constraints. The "Frequency Selective Surface" aspect implies that it is designed to interact with electromagnetic waves at certain frequencies, with Angular Stability Property for performance to be consistent across different incident angles. Such structures are often used in advanced antenna systems, radars, and communication devices where compactness and stability in performance over varying angles are essential. The design and optimization of such structures would likely involve electromagnetic simulation tools and testing to ensure that the miniaturization doesn't compromise the desired frequency response and angular stability.

Focusing on miniaturizing dual-polarized frequency selective rasorber (FSR) with independently regulated dual-transmission response. The proposed design utilizes lumped capacitors and convoluted slot geometries to achieve wideband absorption, in-band transmission, and dual band pass filter capabilities. The FSR operates in the frequency range of 1.87–7.97 GHz and demonstrates angularly stable performance for both TE and TM polarizations. The structure offers a compact geometry and outperforms existing designs in terms of absorption bandwidth and compactness. The performance is verified through simulated and measured results, and the underlying principles of operation are elucidated through equivalent circuit analysis and current distribution. The paper provides a comprehensive overview of the design, analysis, and experimental validation of the proposed miniaturized FSR. Introduction of compact and innovative miniaturized dual-polarized frequency selective rasorber (FSR) with independently regulated dual-transmission response. The proposed FSR design demonstrates wideband absorption, in-band transmission, and dual band pass filter capabilities, operating in the frequency range of 1.87–7.97 GHz. It offers angularly stable performance for both TE and TM polarizations and outperforms existing designs in terms of absorption bandwidth and compactness. The performance of the proposed FSR is validated through simulated and measured results, and the underlying principles are supported by equivalent circuit analysis and current distribution. This work presents a significant advancement in FSR design and offers promising applications in absorptive radome scenarios and wireless propagation systems. Some works provide insights into a compact dual-frequency micro strip branch-line coupler using artificial transmission lines as per Figure 2 below. It discusses the miniaturization process, the layout design, and the simulation results of the proposed coupler. The use of artificial transmission lines contributes to a 70% size reduction compared to traditional designs, with specific characteristics such as a first bandwidth of 59 MHz and a second bandwidth of 37 MHz. The experimental results match well with the simulation results, validating the effectiveness of the compact coupler design. Additionally, the document references relevant works in the field of micro strip branch-line couplers [59].

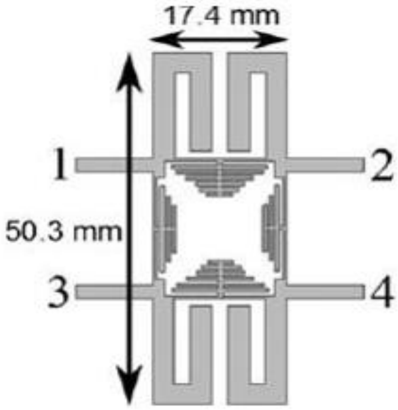


Figure 2: Compact dual-frequency coupler topology [60]

A specific type of electromagnetic structure is designed to selectively filter or manipulate electromagnetic waves at two distinct frequency bands using dual-band Frequency Selective Surface (FSS) is designed to operate in two separate frequency bands. This could be beneficial for applications where filtering or control is needed at multiple frequencies. Frequency Selective Surface (FSS) is a structure that selectively allows or blocks the transmission of electromagnetic waves based on their frequency with designed to be small or have reduced physical size. Compactness is often desirable for applications with space constraints. Ratio between the frequencies of interest is relatively low. In this research analysis also focus on how the frequency of operation impacts the effectiveness of miniaturizing micro strip devices, particularly using artificial transmission lines as well as to investigation into how the effectiveness of miniaturizing micro strip devices is influenced by the operational frequency. Additionally, the study employs artificial transmission lines as a means of experimentation or analysis. Therefore, micro strip devices typically involve components like antennas, filters, or other circuits designed on a micro strip substrate. These are commonly used in high-frequency applications. Implies that the study aims to understand how the operational frequency affects the miniaturization process. Different frequencies may pose unique challenges or opportunities when attempting to miniaturize micro strip devices in artificial transmission lines. Another paper from author Denis A. Letavin discussed on how the frequency of operation affects the efficiency of miniaturizing micro strip devices, particularly when utilizing Low-Pass Filters (LPFs) that suggesting that controlling or understanding the impact of specific frequency components is a key aspect of the research [62]. An approach to miniaturizing the ring shape element of a frequency selective surface (FSS) for X-band signal shielding. The proposed miniaturized ring loop (MRL) FSS is designed to provide attenuation at 10 GHz and is shown to reduce the size of the FSS unit cell by 17.44% compared to conventional ring shape elements. The simulated and measured results demonstrate that the proposed MRL FSS achieves a significant signal attenuation at 10 GHz for both horizontal and vertical polarized electric fields, even at oblique angles up to 45 degrees. The paper highlights the insensitivity of the proposed FSS to changes in the angle of incident and polarizations, making it suitable for applications with limited space for shielding X-band signals. The research is funded by Grant Volt 13H08 (MOHE) and the authors acknowledge the support of various institutions and individuals in conducting this study [63]. Another work related to FSS using 2.5-D knitted structures where it is implies that the structures have some three-dimensional characteristics but are not fully three- dimensional. This research paper suggests the use of materials or designs resembling knitted fabrics, which can be flexible and have intricate patterns [65]. Design approach for a Frequency Selective Surface (FSS) that involves miniaturization and employs a specific structure referred to as Handshake Convoluted Stripe it is specific geometric or structural characteristic resembling a handshake. Where suggests a unique pattern or configuration. A five-order equivalent circuit model, which fits the FSS in the frequency range as wide as 0.1–12 GHz, is presented to get insight into the working mechanism of the proposed FSS. The performances of the FSS are proved by simulations and measurements. The results show that, for both TE and TM modes, the dimension of the dual-polarized element is as compact as 0.0284 λ × 0.0284 λ. The frequency deviation is less than 9 MHz in the incident angle of 0°–60° and polarization angle of 0°–90° [66].

## III. DISCUSSION

In the context of high-frequency applications, such as microwave and radio frequency (RF) communication, miniaturization of transmission lines is crucial. This involves designing compact and efficient transmission lines that can carry signals at higher frequencies without significant signal degradation. The communication presents a novel ultra-wide band frequency selective surface (FSS) with excellent transmission performance in the desired pass band and reflection performance in the out-of-band. The proposed FSS utilizes a cascaded hybrid resonant element composed of resonant circular rings and inductive meandering grid arranged on different layers to achieve wide bandwidth and better band-stop characteristics. Additionally, a fifth-order equivalent circuit model is established to accurately describe the frequency responses of the FSS. The results demonstrate a wide bandwidth, sharp transition, and miniaturization performances, validating the proposed design's ultra-wide bandwidth advantage and excellent out-of-band reflection, steep roll-off, and miniaturization performances. The FSS is validated through simulations and measurements, showcasing its high selectivity and performance in both transmission and reflection [67]. Achieving excellent transmission and reflection performance in an ultra-wide band frequency selective surface (FSS) [68]. The proposed design employs a cascaded hybrid resonant element and a fifth-order equivalent circuit model to accurately describe the frequency responses. The results show a wide bandwidth, sharp transition, and miniaturization performances. The bandwidth achieved by the proposed ultra-wide band FSS is 154.4 % from 0.5 to 3.88 GHz, and -10 dB stop band is from 4.04 to 7.68 GHz with a sharp transition within 160 MHz from pass band to stop band. Miniaturized FSS appears to be a novel design that leverages a convoluted element of dipoles. The fractional bandwidth of the FSS is highlighted. At normal incidence, the fractional bandwidth increases to 57 %, indicating that the FSS can operate effectively over a relatively wide range of frequencies. For oblique incidence up to 60°, the fractional bandwidth remains substantial at 33%. Its key features include miniaturization, stability under varying conditions, and a substantial fractional bandwidth. This type of FSS design could find applications in various fields, such as antennas, communication systems, or electromagnetic shielding, where miniaturization and broadband performance are essential. The use of dipoles and the convoluted structure may contribute to achieving the desired electromagnetic properties [69]. Size reduction in millimetre-wave frequency doublers is important. It is necessary to evaluate performance of 40 GHz frequency doubler using artificial transmission lines (ATLs) to minimize the size of low-impedance shunt stubs. The paper demonstrates the use of ATLs in the design of low-impedance stubs, which resulted in a significant reduction in size while maintaining high performance [70]. The developed frequency doubler exhibited state-of-the-art conversion loss and rejection of the fundamental frequency signal, making it suitable for integration into millimetre- wave systems. The paper also introduces a new simulation method for the design of frequency multipliers and provides theoretical design considerations for ATL stubs, verified through electromagnetic simulations. Overall, the miniaturized ATL frequency doubler offers high efficiency, low area requirement, and over 20-dB rejection of the fundamental signal, making it a promising building block for the generation of local-oscillator signals in millimetre-wave systems.

## IV. CONCLUSION

Miniaturization is an important technological innovation that tends to reduce the size of circuits and lines without negatively affecting the performance of components and products. The innovation uses several approaches to shrink size such as; met materials, minimizing number of devices, space adjustment, circuit modification, material loading, and so on. Miniaturization usually manipulates electromagnetic properties of materials at the scale of sub-wavelengths. The met materials are materials with supernatural properties that make it possible to be shrink to small- size in the design of antennas, filters, controllers, sensors, and so on. It has significant impact on energy usage across components by supporting effective use of energy. Miniaturization is a key concept in microelectronic circuits where there is need reduce size of components, improve performance, save energy, and offer wide range of frequencies. Miniaturization is highly effective resources are scares and require responsible utilization like in the case of in microwave and RF transmission lines.

### *A. Conflict of Interest*

The authors declare no conflicting interests and all authors have agreed to this submission.

### *B. Conflict of Interest*

No funding is received for this work.

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