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Embroidered Dual Band Wearable Microstrip Patch Antenna

Jayant G. Joshi[1], Mandar P. Joshi[2*], Shyam S. Pattnaik[3]

[1]Department of E & TC Engineering, Government Polytechnic, Nashik, India

[2] Department of E & TC Engineering, GES's R. H. Sapat College of Engineering, Management Studies and Research, Nashik, India

[3] E & C Department, National Institute of Technical Teachers Training and Research, Chandigarh, India

Email: jgjoshiantenna@gmail.com, mandarjoshi11@gmail.com, profshyampattnaik@gmail.com

*** Corresponding author's e-mail address:** mandarjoshi11@gmail.com

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Abstract: This research study presents an embroidered polyester-based dual band rectangular slotted wearable microstrip patch antenna for WLAN spectrum applications. To obtain the dual frequency bands, a slotted rectangular microstrip patch is coupled to an interdigital capacitor (IDC). The antenna exhibits a 4.97 GHz resonance frequency with a bandwidth of 100 MHz and a gain of 6.60 dBi. Additionally, this antenna has a gain of 7.85 dBi, a bandwidth of 390 MHz, and a resonance frequency of 5.59 GHz. The antenna has been constructed, tested, and the research paper's measurements show the outcomes. The results from simulation and measurement are discovered to be in good agreement. Additionally, a created and examined equivalent circuit of the antenna is presented in this paper.

Keywords: Embroidered, wearable, polyester, interdigital capacitor, public safety band

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1. INTRODUCTION

Recently, especially in the personal area and body area networks, body-centric communication has huge potential under 4G/5G communication systems. It creates wireless connections between (a) devices that are mounted on the body, (b) devices that are worn on the body, and (c) off-body devices, such as base stations and mobile devices, (d) medical systems that use implantable gadgets or sensors [1-4]. Wearable computers, flexible mobile phones, PDAs, smartphones, tablet computers, biotelemetry sensors, and other items used by the military and police are just a few examples of some of these devices. The military, firefighters, and police utilize these systems to protect people and property and to keep an eye on important areas like airports, seaports, and shopping centres, among others.. These gadgets might be the user or wearer's garments, or they could be worn under, over, or in clothing. It covers a variety of bands, including the public safety band, body area network, industrial scientific and medical, wireless local area network, Wireless Fidelity, Bluetooth, and HYPER LAN.

Wearable antennas are an integral part of user clothing and are produced from a range of textile/cloth-based materials, such as cotton, Nomex, liquid crystal polymer, foam, Nomex, fleece fabric, nylon, and polyester, conducting ribbon, insulated wire, conducting paint, copper-coated fabric, geotextile, etc. Wearable antennas are also used in a variety of other applications. In the literature, a variety of wearable antennas have been discussed [1-4]. These antennas have been created for body-centric communication systems, including Wi-Fi, WiMAX, WLAN, HYPER LAN, BAN, and Bluetooth applications, on a variety of textile substrates. A study on the demand for wearable antennas for the ISM, BAN and PAN applications was provided by Hall P. S. and Hao Y in Ref [1]. The authors of [2] described a wearable rectangular microstrip antenna for IEEE 802.11a WLAN applications. The wearable antenna using a geotextile substrate is reported for applications in public safety in Ref. [3]. In order to make wearable antennas simple to include in clothing and wearable devices, researchers are employing a wide variety of strategies to enhance their design and function. One of the most modern methods for creating wearable antenna patches that are small, strong, and lightweight is embroidery. In wireless communication networks, embroidered antennas are becoming more and more common. Numerous embroidered antenna configurations have been documented in the literature [5–8]. Shiya Zang et al. reported that the embroidery antenna could be constructed using stitching on cloth material. The patch antenna was created using amberstrand silver-coated fibre for 1.39 GHz applications [5]. For applications in the ISM North and South America 902-928 MHz band and the European Free Industrial Scientific and Medical (ISM) 863-870 MHz band, Theodoros N. Kapetanakis et al. presented an embroidered Sierpinski triangle Bow-tie antenna arrangement [6]. In this study, the antenna is constructed on a Nomex substrate using a 4-strand silver hybrid thread [6]. A stitched circular microstrip patch antenna for UWB applications between 3.1 GHz and 10.6 GHz was presented by Shakhirul, M.S. et al. [7]. Syscom Advanced material Amberstrand 166 and Liberator 40 threads were used to fabricate this antenna. On a 0.25 mm thick Calico textile substrate, Michael Elsdon et al. reported an embroidered slot-loaded rectangular microstrip patch antenna for 1.97 GHz [8]. The patch was fabricated by conductive Nora Dell material. Different configurations of slotted rectangular and circular disc multi-band microstrip patch antennas have been reported in Refs. [9-10]. For 5.8 GHz applications, a quasi-lumped IDC resonator antenna is given in Ref. [11]. In Ref. [12], the impact of the human body on the performance of patch antennas is covered. Symmetrically cut electrically small hand-fan-shaped monopole antenna for wideband wireless applications has been presented in Ref. [13]. Slot-cut nested polygonal shaped microstrip antenna for ultra wideband application has been reported using thinner substrate in Ref. [14]. The goal of this research is to create a slotted rectangular microstrip patch using embroidery technology in order to obtain dual frequency bands and minimize the patch's metal content. Second, by adjusting the design parameters of the IDC, it is possible to achieve the application-based frequency bands and bandwidth by connecting an IDC to a slotted patch. For public safety band and WLAN applications, the authors of this work proposed an embroidered polyester (textile) based dual-band wearable slotted microstrip antenna coupled with IDC. In order to safeguard human life, health, and property, the Federal Communication Commission (FCC) has designated a specific frequency range, measuring 4.94 GHz to 4.99 GHz, as a 50 MHz band. It includes applications for ambulance services, off-site personnel and rescue teams, police cars, fire trucks, and police vehicles. IEEE 802.11a for WLAN applications also covers the 5 GHz band ranges.

2. ANTENNA STRUCTURE DESIGN

Figure 1 shows a geometrical construction of a wearable microstrip antenna with rectangular slots made of copper tape on a polyester substrate. The photographs of the antenna's top side and bottom side are shown in Figures 2(a) and 2(b), respectively. The rectangular patch has the following dimensions: length L_m = 30 mm and width W_m = 20 mm. The IDC has been connected to the slotted rectangle patch to obtain the desired frequency bands. Figure 3 presents a sketch and geometrical structure of IDC. The IDC has the following dimensions: finger length C_L = 6 mm, finger width w = 2, tooth spacing s = 1, and number of finger pairs N = 6. A pair of rectangular parallel slots is cut inside a rectangular patch with a spacing of $\lambda g/10$. A slot of rectangle shape with dimensions length x = 11 mm and width y = 2 mm is cut at the center of the rectangular patch. Second slot of sizes length a = 10 mm and width b = 5 mm is cut in the patch at a distance of 4.5 mm from the first slot. The second slot's distance from the rectangular patch's boundary is set at $\lambda g/10$. The polyester textile substrate's height and dielectric constant are 3.14 mm and 1.39, respectively. The polyester fabric layers are cut and sewn together to create the substrate of the specified thickness. As shown in Figure 2(a), the patch is sewn onto the polyester dielectric substrate using conductive copper thread at closer intervals to increase electrical conduction. Two parallel stitches are spaced apart by 0.2 mm. Both rectangular slots have been correctly embroidered during the embroidery process using geometrical dimensions. During the embroidery process, the exact dimensions of the IDC fingers are maintained, and they are perfectly attached to the slotted rectangular patch. The ground plane is constructed using self-adhesive copper tape with a thickness of 0.1, as shown in Figure 2(b). In order to keep the copper thread and ground plane composed of copper tape from contaminating each other during the embroidery process, a polyester layer is put between the copper thread and the polyester substrate. The polyester substrate is kept at a thickness of 3.14 mm during the whole production process. A 50Ω coax connector and cable were used to feed the antenna.

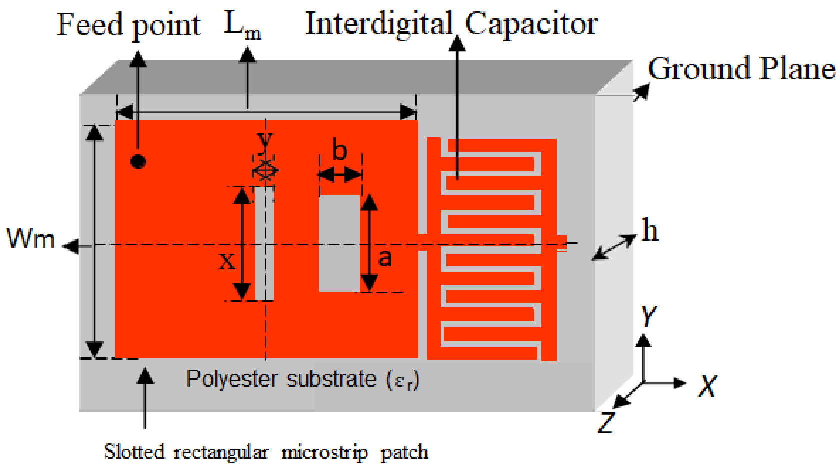


Figure 1. Geometrical construction of embroidered polyester-based rectangular antenna.

(a) (b)

Figure 2. Photographs of fabricated embroidered wearable antenna (a) Top side (b) Bottom side.

The dimensions and locations of rectangular slots are selected in such a way that the current path lengths change for the two modes in a different ratio to obtain the desired frequency ratio of dual-band operation. In the present case, the frequency ratio is 1.14, which is smaller than the ratio of 3 for the rectangular microstrip antenna (RMSA) without slots. This frequency ratio is approximately equal to the L/W ratio of a rectangular microstrip patch antenna. IE3D electromagnetic simulator is used to simulate this antenna. The benefits of the proposed antenna are as follows: (a) in the presented design, both slots make the proposed antenna compact and provide dual-band performance. Due to slots, metal from the radiating element has been removed. Therefore, a small section of the presented antenna having slots, as opposed to the traditional rectangular microstrip patch (without slots), bends as a result of movement of the body. (b) This geometry is beneficial for reducing the electromagnetic field absorption in the tissues of the human body since it reduces the metal part of the patch. (c) Flexibility to adjust the required resonant frequency bands by varying design parameters of IDC.

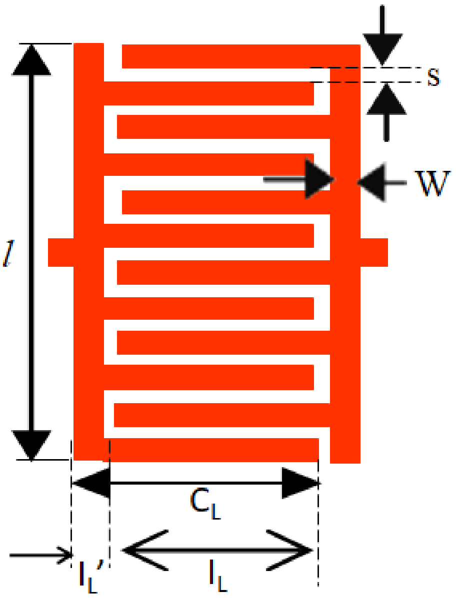


Figure 3. Sketch and geometrical structure of interdigital capacitor (IDC).

3. RESULTS AND DISCUSSION

Figure 4 shows the simulated reflection coefficient (S_{11}) characteristics of the rectangular slotted microstrip patch antenna. The antenna is seen to resonate at two different frequencies, 4.8 GHz and 8 GHz, respectively. However, these two bands are not according to the application requirement, public safety and WLAN bands. Hence, an IDC is connected to a slotted rectangular antenna to tune it to the required dual frequency bands. Figure 5 presents the simulated reflection coefficient (S_{11}) characteristics of the proposed antenna when IDC is connected to a slotted rectangular microstrip radiator. This antenna has a 100 MHz bandwidth and resonates at 4.97 GHz. Additionally, the antenna has a second resonance frequency of 5.59 GHz with a bandwidth of 391 MHz (7%). Figure 6 shows the measured reflection coefficient (S_{11}) characteristics along with a picture of the experimental setup used to measure the antenna's return loss. Antenna measurement is carried out using the Agilent Technologies Keysight RF Vector network analyzer N9923A. This antenna resonates at 4.84 GHz. Furthermore, the antenna has a second resonance frequency of 5.53 GHz with a bandwidth of 313 MHz (6%). There is agreement between the outcomes of simulated and measured results.

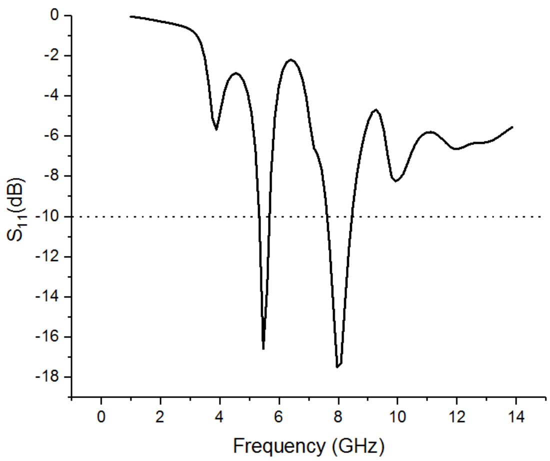


Figure 4. Simulated reflection coefficient (S_{11}) graph of a rectangular slotted wearable microstrip patch antenna without IDC.

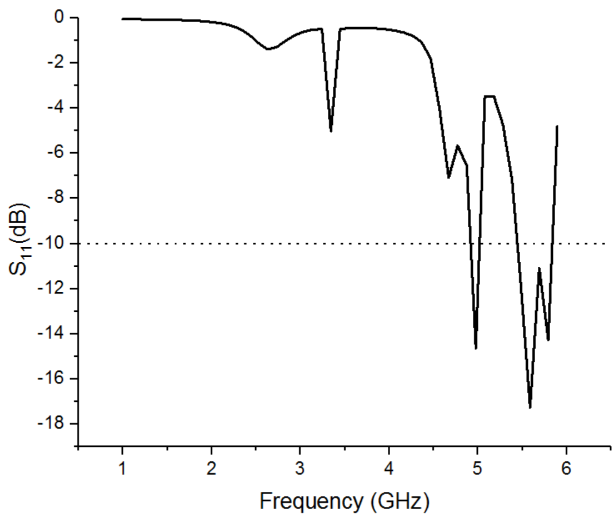


Figure 5. Simulated reflection coefficient (S_{11}) characteristics of rectangular slotted wearable microstrip patch antenna with IDC.

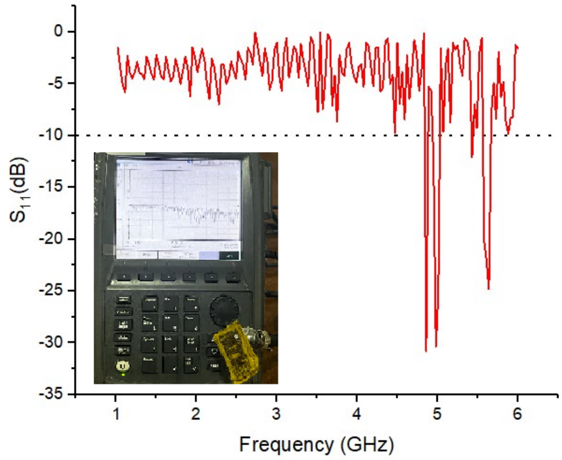
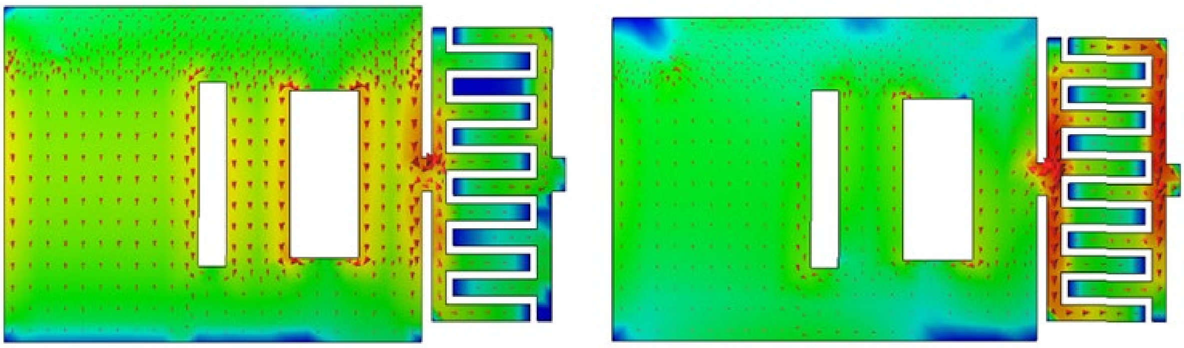


Figure 6. Measured reflection coefficient (S_{11}) characteristics of rectangular slotted wearable microstrip patch antenna with IDC.

Figure 7 shows surface current distribution along the antenna structure for WLAN and public safety using the IE3D electromagnetic simulator at (a) 5.59 GHz, (b) 4.97 GHz. It has been observed that, at 4.94 GHz, the current encircles around both slots and is more concentrated around the finite lengths of slots. Which results in the enhancement of the electrical length of the antenna. IDC's fingers have an even distribution of the current.



(a) (b)

Figure 7. Surface current distribution (a) 5.59 GHz (b) 4.97 GHz.

The presented wearable microstrip patch antenna's azimuth and elevation radiation patterns at 4.97 GHz and 5.59 GHz are shown in Figures 8(a) and 8(b), respectively, and show gains of 6.60 dBi and 7.85 dBi, respectively.

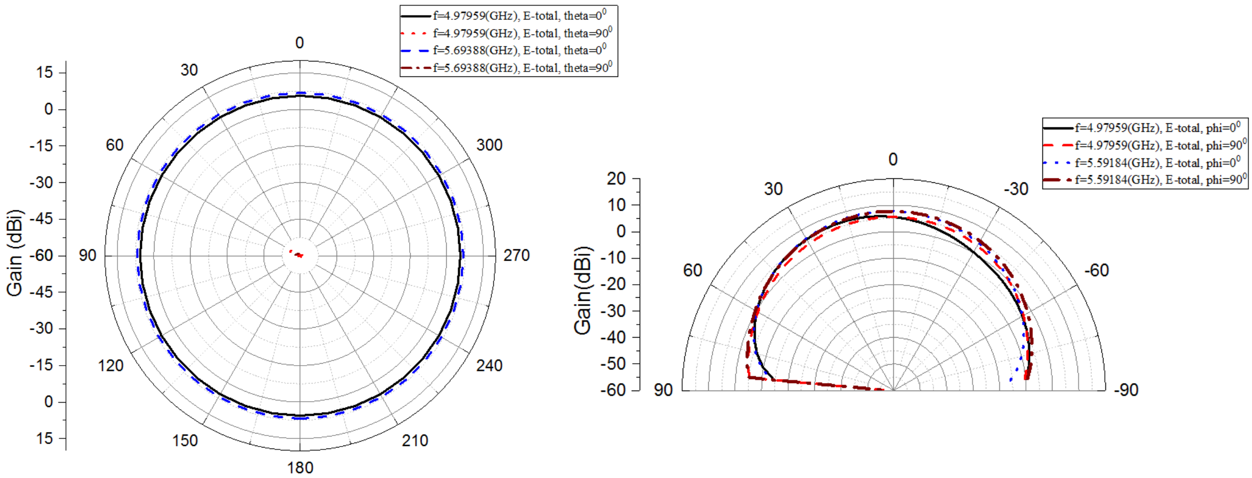


Figure 8. Radiation patterns of proposed wearable microstrip patch antenna (a) Azimuth (b) Elevation.

A comparison of the proposed antenna and the reported embroidered antennas from the literature is shown in Table 1.

Table 1. Comparison between proposed antenna with reported antennas

Ref	Antenna Design	Substrate Material	Relative permittivity (ε_r)	Substrate thickness (h) mm	Bandwidth (MHz)	Gain (dBi)	Application
[6]	Bow-Tie	Nomex	3.5	1	13	1.21	ISM
[7]	T-shaped slot	Cotton	1.6	0.5	7500	1.7	UWB
This work	Rectangular slotted Patch loaded with IDC	Polyester	3.14	1.39	100 & 391	6.6 & 7.85	Public safety & WLAN

4. EQUIVALENT CIRCUIT

Figure 9 depicts equivalent circuit diagrams of the proposed antenna. An antenna is effectively an LC resonant circuit, where L and C stand for the antenna structure's equivalent inductance and capacitance. The slotted antenna without IDC resonates at WLAN and X-bands. When IDC is coupled in series with the RLC equivalent circuit of a slotted rectangular microstrip patch antenna, it gets tuned to the public safety band, keeping WLAN band the same. Thus, the frequency bands of interest have been obtained. The equivalent circuit elements' details are as follows.

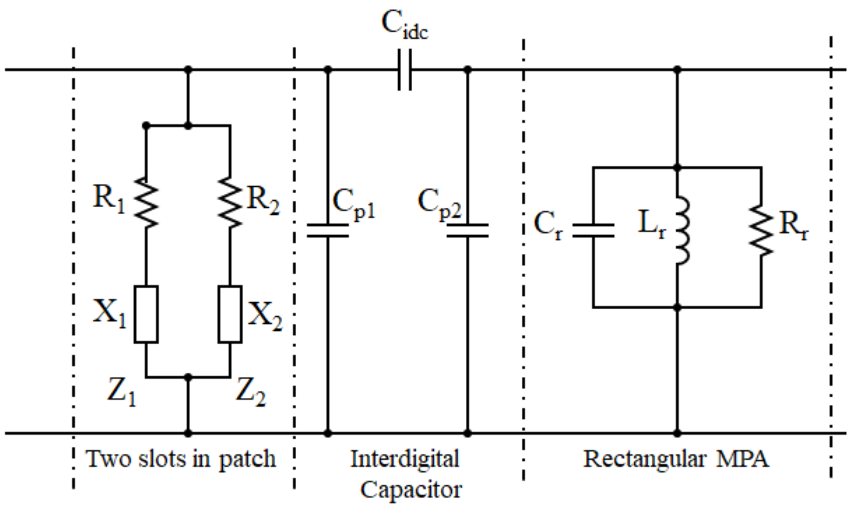


Figure 9. Equivalent circuit schematic for the proposed antenna

R_r, L_r and C_r: Resistance, Inductance and capacitance of rectangular microstrip patch antenna, respectively

R_1 and R_2: Radiation resistances of first and second slots, respectively

X_1 and X_2: Reactive components of first and second slots, respectively

C_{p1} and C_{p2}: Pad Capacitors due to pads connected at both ends of IDC, respectively

IDC is a periodic structure that comprises narrow gaps of a number of conductors i.e. multi-finger between which the capacitance occurs. This capacitance can be increased by increasing the number of fingers. Capacitance of interdigital capacitor (C_{idc}) is calculated using Equ. (1) (Ref. Figure3) [11].

$$C_{idc} = \varepsilon_0 \left(\frac{\varepsilon_r+1}{2}\right)[(N-\Delta)C_L] \quad (1)$$

Where, C_L is physical length of overlapping width of interdigital finger. Δ is width correction factor expressed by equation $\Delta = 0.5(W_{eff} - w')$ and $w' = 2 \times I_L' + I_L$. W_{eff} is the effective corrected transmission line width with the value of 1.5×10^{-3}. C_{p1} and C_{p2} are pad capacitances connected at both ends of the structure and calculated using Equ. (2) [11].

$$C_p = \left[\frac{2.85\varepsilon_{eff}}{\ln\left[1+\left(\frac{1}{2}\right)\left({}^{8h}/_{w_{eff}}\right)\left[\left({}^{8h}/_{w_{eff}}\right)+\sqrt{\left({}^{8h}/_{w_{eff}}\right)^2+\pi^2}\right]\right]}\right] \times \left[\frac{1}{25.4\times10^{-3}}\right] \quad (2)$$

Where,

ε_{eff} is the effective relative permittivity of the substrate and is estimated using Equ. (3).

$$\varepsilon_{eff} = \left(\frac{\varepsilon_r+1}{2}\right)\left(\frac{\varepsilon_r-1}{2}\right)\left[1+\frac{10h}{w}\right]^{-0.5} \quad (3)$$

The calculated values of C_{idc} and C_p are 0.189 pF and 1.179 pF, respectively. These capacitance values of IDC fine-tune the proposed antenna to public safety and WLAN bands.

5. CONCLUSION

An embroidered dual-band polyester wearable microstrip patch antenna for WLAN band applications is reported in this research. The attached IDC add series capacitance to the slotted rectangular microstrip patch's LC resonant circuit. It has been discovered that connecting IDC is a helpful strategy for obtaining the frequency bands and bandwidth with regard to applications. The suggested embroidered antennas simulated and measured frequency bands are obtained to be in agreement. This antenna's lightweight, ease of construction, mechanical robustness, and affordability are important characteristics. By changing the design parameters and the location of the IDC, the authors have expanded their research to better understand the impact on the resonance frequency, bandwidth, and gain of the proposed antenna.

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