Peer-reviewed version available at Electronics 2018, 8, 11; doi:10.3390/electronics8010011

Type of the Paper (Article)

Meander microwave bandpass filter on flexible textile substrate

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Abstract: This paper presents an alternative process to fabricate flexible bandpass filters by using embroidered yarn conductor on electronic-textile. The novelty of the proposed miniaturized filter is its complete integration on the outfit, with benefits in terms of compressibility, stretch ability and high geometrical accuracy, opening the way to develop textile filters in sport and medicine wearable applications. The proposed design consists of a fully embroidered microstrip topology with a length equal to quarter wavelength ($\lambda/4$) to develop a bandpass filter frequency response. A drastic reduction in size of the filter was achieved by taking advantage of a simplified architecture based on meandered-line stepped impedance resonator. The e-textile microstrip filter has been designed, simulated, fabricated and measured, with experimental validation at a 7.58 GHz frequency. The insertion loss obtained by simulation of the filter is substantially small. The return loss is greater than 20 dB for bands. To explore the relations between physical parameters and filter performance characteristics, theoretical equivalent circuit model of the filter constituent components were studied. The effect of bending of the e-textile filter is also studied. The results show that by changing the radius of bending up to 40 mm, the resonance frequency is shifted up 4.25 MHz/mm.

Keywords: Band-pass filter, E-textile, Stepped impedance resonator, Meandered resonator

1. Introduction

Microwave band pass filters (BPF) are key building elements of communication systems. They should satisfy severe requirements, mainly system performance frequency response, reduced size, and manufacturing cost. Nowadays, several researches in the microwave domain are focused on BPF size miniaturization and integration.

Recently, it is desirable to develop new type of microstrip band pass filters with small size and planar fabrication. Parallel coupled microstrip band pass filters are common elements in many microwave systems [1], due to their advantages such as planar design, easy analysis and low cost. A type of miniaturized microstrip band pass filter by using pseudo-interdigital structure without via holes ground is proposed in [1] and a variety of resonator types have been introduced including split-ring resonators [2] or stepped impedance resonators (SIR) [3] to achieve band pass filter frequency responses.

On the other hand, wearable technology has been widely developed and deeply studied in recent years. It has been adopted in many applications including on-body networks [4], location tracking [5], fitness monitoring [6], and e-textile metamaterial signal propagation control [7]. The common features of e-textile systems are low-profile, light-weight, wireless connection and multi functionality, required by modern wearable applications.

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In this paper, we present for the first time an e-textile microwave filter based on embroidered meander microstrip line. The new microstrip filter structure has advantages in terms of compressibility, stretchability, and high duration to repetitive deformations. Results demonstrate that the new textile filter has comparable performance to their conventional counterparts implemented on conventional printed circuit board (PCB) substrates.

The main novelty of the paper consists of utilizing textile material as substrate to develop a meander filter at the microwave frequency band. In comparison with conventional devices, the proposed filter has the ability of controllable electromagnetic properties and device flexibility. Furthermore, the proposed filter guarantees a band pass from 7.17 to 8 GHz with return loss lower than -30 dB.

The e-textile filter has been simulated, fabricated and measured in the bandwidth delimited by 7.17-8 GHz with center frequency at 7.58 GHz.

The remainder of the paper is organized as follows. Section 2 describes the theoretical framework of the proposed wearable meander microwave filter. In Section 3 the filter implementation and experimental results are shown and discussed. In Section 4, the bending effects on the filter performance are analysed experimentally. Finally, in Section 5 the conclusions of this work are summarized.

2. THEORETICAL FRAMEWORK

The proposed band pass filter (BPF) is designed on an e-textile felt substrate with characterized h = 1 mm thickness, dielectric constant $\varepsilon_r = 1.2$, and loss tangent tan δ = 0.0013. In order to determine the substrate dielectric constant and loss tangent of felt substrate, the resonance method based on a split post dielectric resonator (SPDR) measurement has been carried out.

The filter is designed using a quarter wavelength (λ/4) microstrip with different characteristics impedance of the line to achieve stepped impedance.

Since most filters are composed of linear components based on simple and fast computer-aided network analyses, let us consider at first the stepped impedance resonators (SIR) concept. SIT allows to establish a relation between the linear elements equivalent circuit model and the layout of physical dimensions.

A microstrip stepped impedance resonator is formed by joining two transmission line with different characteristic impedances, Z_1 and Z_2, with corresponding electrical length θ_1 and θ_2, respectively [8], as shown in Figure 1. Resonant condition of the SIR depends on value of θ_1, θ_2 and R. Furthermore, the analytical models are used to compute the circuit parameters at 7.58 GHz central frequency. The total electrical length of the structural fundamental is given by [9] which is $\theta_t = \theta_1 + \theta_2, K < 1$. The resonance condition of an SIR will occur when,

$$K = \tan\theta_1 \tan\theta_2 = \frac{Z_1}{Z_2} \qquad (1)$$

Where K is impedance ratio. For this design we have considered K=0.4. The characteristic impedance of lines are designed at Z_1 =50 Ω, Z_2 =121 Ω and electrical lengths of line are θ_1=31°, θ_2=79°.

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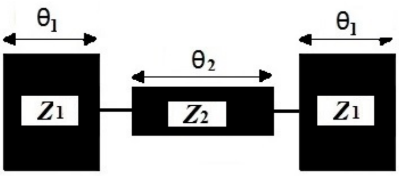

Figure 1. Configuration of the basic structure of the stepped impedance resonator (SIR), where $K = \frac{Z_1}{Z_2} < 1$.

The typical structure of the SIR as shown in Figure 1 can be mathematically verified by solving this electrical network using circuit theory. Over all ABCD parameters of this circuit are calculated by calculating ABCD parameters of the individual stepped. The ABCD parameters of the circuit can be determined by [10], as follows:

$$\begin{pmatrix} A & B \\ C & D \end{pmatrix}_{Overall} = \begin{pmatrix} \cos\theta_1 & jZ_1\sin\theta_1 \\ \frac{j\sin\theta_1}{Z_1} & \cos\theta_1 \end{pmatrix}_{step1} \begin{pmatrix} \cos\theta_2 & jZ_2\sin\theta_2 \\ \frac{j\sin\theta_2}{Z_2} & \cos\theta_2 \end{pmatrix}_{step2} \begin{pmatrix} \cos\theta_1 & jZ_1\sin\theta_1 \\ \frac{j\sin\theta_1}{Z_1} & \cos\theta_1 \end{pmatrix}_{step1} \quad (2)$$

Where, A, B, C, and D are the network parameters of the transmission matrix, which is the result of the multiplication of the three ABCD matrices corresponding to network of Figure 1.

In order to reduce the filter size, in next step the meandered line SIR was considered. The layout of the proposed filter is illustrated in Figure 2 (a) that, the line width for microstrip is chosen as W_1 = 4 mm, which gives characteristic impedance Z_0 = 50 ohm on the substrate. The detailed dimensions are as follows: L_{s1}=3.26 mm, L_{s2} = 18.5 mm, L_{s3} = 1.5 mm, and spacing between two meander lines S = 1.5 mm. Also width for microstrip quarter -wavelength resonators is chosen as W_2= 0.5 mm.

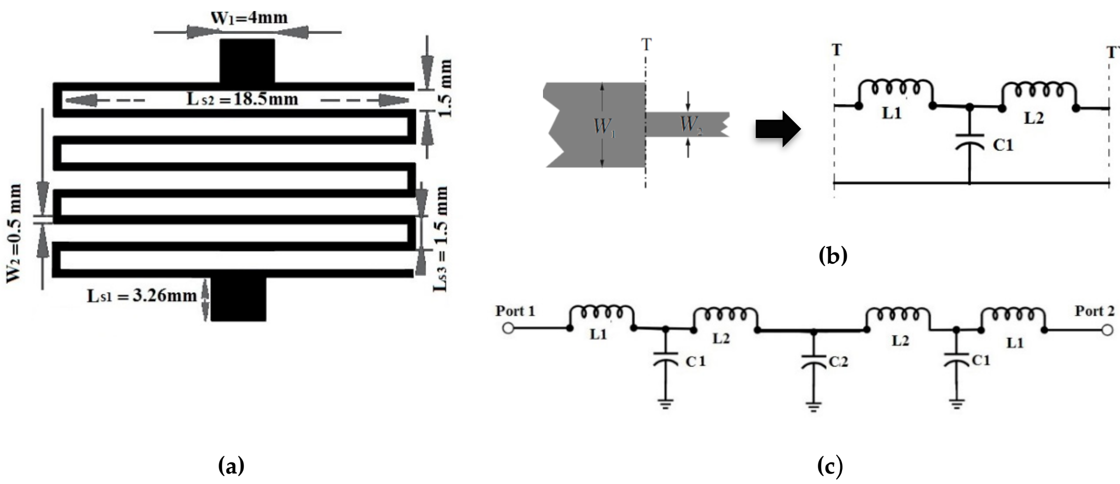

Figure 2. (a) Layout of the proposed e-textile meander microstrip line. **(b)** Capacitance and inductances of the equivalent circuits for the subnetworks for symmetrical steps. **(c)** Equivalent circuit model of network.

The equivalent circuit model of a filter helps to understand the behavior of the design. As illustrated in Figure 2(b), the subnetwork can be represented by L-C circuit and the values of L and C of individual steps is calculated by the use of standard equations in [8]. For the symmetrical microstrip steps the subnetworks is described by capacitance (C_1) and inductances (L_1, L_2) corresponding to equivalent circuit shown in Figure 2(b). In the other hand, the proposed meander microstrip lines

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acts as a resonant (L_2C_2) circuit. The vertical elements act as the inductor, horizontal elements act as capacitor. The overall electrical equivalent circuit of the proposed filter structure which is shown in Figure 2(c) can be obtained by combining the equivalent circuits of symmetrical steps and meander microstrip lines. This circuit is simulated by Advanced Design System (ADS) simulator and its frequency response is compared with full 3D electromagnetic CST Microwave Studio 2018 software. The capacitance and inductances of the equivalent circuit indicated in Figure 2(c) can be approximated by the following formulation [8].

$$C_1 = 0.00137h\frac{\sqrt{\varepsilon_{re}}}{Z_{c1}}\left(1-\frac{W_2}{W_1}\right)\left(\frac{\varepsilon_{re1}+0.3}{\varepsilon_{re1}-0.258}\right)\left(\frac{W_1/h+0.264}{W_1/h+0.8}\right)\ (pF) \quad (3)$$

The estimation of the capacitance of the interdigital layout can be given by

$$C_2 = 3.937\times 10^{-5} l\ (\varepsilon_r+1)(0.11(N-3)+0.252)\ (pF) \quad (4)$$

The total length is given by $\frac{\lambda_0}{4} = \mathrm{NL}_2 + (\mathrm{N}-1)\mathrm{S}$ where N number of turns, S is spacing between two meander lines. The inductance per unit length is calculated as follows [8]:

$$L = 0.000987h\left(1-\frac{Z_{c1}}{Z_{c2}}\sqrt{\frac{\varepsilon_{re1}}{\varepsilon_{re2}}}\right)^2\ (\mathrm{nH}) \quad (5)$$

$$L_{w1} = \frac{Z_{c1}\sqrt{\varepsilon_{re1}}}{c}\ and\ L_{w2} = \frac{Z_{c2}\sqrt{\varepsilon_{re2}}}{c} \quad (6)$$

Where L_{wi} for i = 1, 2 are the inductances per unit length, having widths W_1 and W_2, respectively. While Z_{Ci} and ε_{rei} denote the characteristic impedance and effective dielectric constant corresponding to width W_i and c is the light velocity in free space.

$$L_1 = \frac{L_{w1}}{L_{w1}+L_{w2}}L\ (\mathrm{nH}) \quad \text{and} \quad L_2 = \frac{L_{w2}}{L_{w1}+L_{w2}}L\ (\mathrm{nH}) \quad (7)$$

The values of the different parameters can be initially estimated from the physical dimensions, but at the end there will be necessary to optimize them by a tuning procedeure to fit the measured response.

3. Filter Implementation and Results

The fabric structure was a non-woven structure with a 100% polyester composition. These textile substrates are resistant to sweat and humidity and they offer some key advantages, including durability, chemical moisture resistance, and heat stability. The weight is 211 g/m2, and the structure is a double-sided needle punching.

The selected conductor yarn corresponds to a commercial Shieldex Plated Nylon 66 Yarn 117/17 dtex 2- ply and it is composed by 99% pure silver plated nylon yarn 140/17 dtex with a linear resistance < 30 Ω/cm. The used stitch type corresponds to the ISO 4915:1991 301 standard.

The conductive thread is relatively thick compared to the conventional embroidery thread, due to the mechanical restrictions of the embroidery machine. In order to optimize the fabrication process the conductive thread has been used in the bobbin of the embroidery machine whereas a conventional embroidery yarn has been considered for the upper thread. A certain degree of tension control in the upper thread is carried out in order to increase the accuracy of the stitching geometries and patterns. The stitch spacing corresponds to the distance between two needle penetrations on the same side of a column. The homogeneous layout is converted to a stitch pattern by using the *Digitizer Ex* software for fabrication process. This software package is used to create the stitch pattern, which is then exported to the embroidery machine and stitched. A *Singer Futura XL-550* embroidery machine has been used to manufacture the prototype.

doi:10.20944/preprints201811.0449.v1

Peer-reviewed version available at *Electronics* **2018**, *8*, 11; doi:10.3390/electronics8010011

The proposed design has been embroidered with satin pattern with 60% density. The density determines the gap between stitches. For narrow columns, stitches are tight, thus requiring fewer stitches to cover the fabric. In areas with very narrow columns, less dense stitches are required because too many needle penetrations can damage the textile sample. Indeed by increasing embroidering density boost surface conductivity.

The ground plane had been chosen as a homogeneous uniform commercial *WE-CF* adhesive copper sheet layer (constant thickness t = 35 μm).

Figure 3 shows the photograph of the BPF embroidered wearable prototype. The idea is to use e-textile to enable low embroidery tension and high flexibility, improving the embroidery process. The fabricated filter satisfied the requirements of providing the wearer with such compact size, flexible materials, ease of washing, and very attractive wearable application.

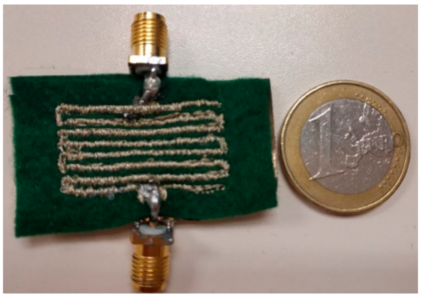
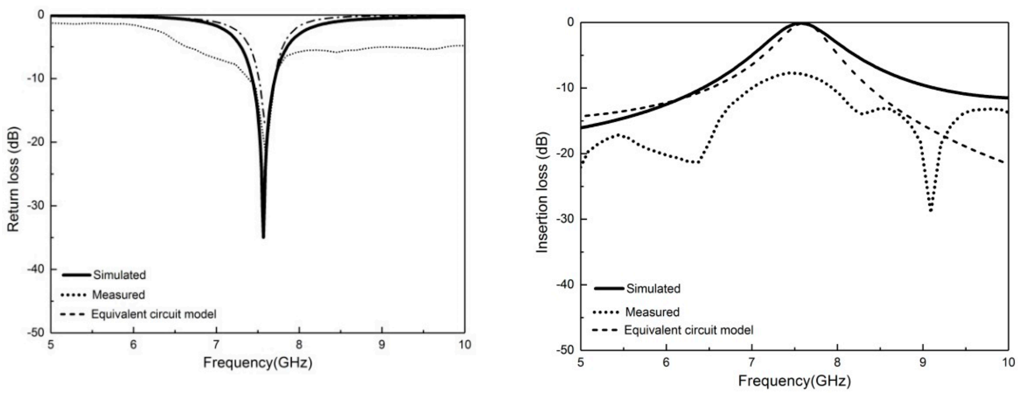


Figure 3. Photograph of the embroidered design.

Figure 4 shows the comparison between the simulated and measured frequency responses of insertion losses (S_{21}) return losses (S_{11}). The S_{21} and S_{11} were tested up to 10 GHz by means of a microwave analyzer, *N9916A FieldFox* (Keysight, Santa Rosa, CA, USA), operating as a vector network analyzer.

As illustrated in Figures 4(a, b), the bandwidth of the simulated and equivalent circuit model results was in the range between 7.17 GHz and 8 GHz. Furthermore, there is a clear relationship between the equivalent circuit model and the layout physical dimensions.

The simulated and equivalent circuit model of proposed circuit presents good electrical performances with an insertion loss of -0.5 dB and a return loss of -30 dB at the frequency (7.58 GHz), whereas the measured insertion loss and the return loss are about -11dB and -29 dB respectively. The discrepancy between simulated and measured results is due to fabrication tolerances, thickness of the adhesive that was used for ground layer, and improper soldering of connector as well as the lack of homogeneity of the embroidery, in comparison with standard PCB metallization. Nevertheless, the bandpass behavior is clearly defined and can be boosted by a conventional amplification technique.



(a) **(b)**

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Figure 4. Comparison between insertion loss and the return loss measured, electromagnetically simulated and equivalent circuit response of band pass filter.

The equivalent circuit parameters are extracted from optimization of circuit to fit with the simulated and measured response. Table I shows a summary of parameters corresponding to capacitance and inductances parameters of Figure 2(c), for the best fit we have been able to find in simulation and theoretical point of view.

Table I: Comparison of equivalent circuit model parameters in simulation (ADS) and theoretical of band pass filter

Comparison	L_1(nH)	L_2 (nH)	C_1(pF)	C_2(pF)
Theoretical parameters	0.96	2.32	$1.7e^{-6}$	1.1
Optimized Parameters	0.03	6.4	$0.05e^{-6}$	0.13

4. Bending Effects

In wearable systems, it is very difficult to keep the substrate in a flat configuration all the time, especially when the prototype is made of textile materials and it is frequently bent due to human body morphology and movements. Therefore, it is necessary to investigate the prototype performance characteristics under bending conditions. Figure 5 shows the output characteristic of the proposed BPF under bending condition.

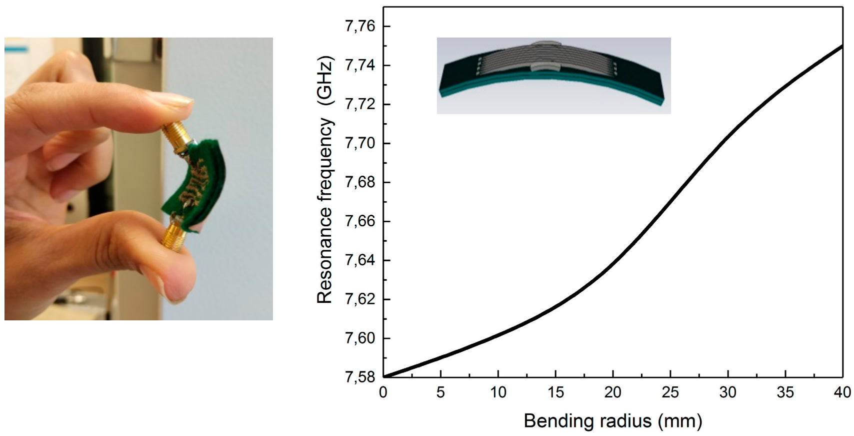

Figure 5. Simulated effect of bending of wearable filter with different radii: 10, 30 and 40 mm.

It is observed that by changing the radius of bending to 40 mm, the resonant frequency is shifted up 4.25 MHz/mm

5. Conclusions

A compact e-textile bandpass filter has been designed and successfully fabricated and tested. The proposed design is a fully embroidered conductive thread meander microstrip on textile substrate. A significant agreement is achieved for the EM layout simulations, equivalent circuit model and the experimental results. The measurement results exhibit a well-defined band-pass at center frequency of 7.58 GHz, with return loss of -29 dB and -11 dB for the insertion loss while, simulated return loss response is -35 dB and insertion loss is - 0.5 dB. The proposed filter has advantages of miniature size, flexible, durable and ease of washing and also suitable for applications in health management based on signal monitoring and sports.

Funding: This research was funded by the Spanish Government MINECO under Project TEC2016-79465-R.

Conflicts of Interest: The authors declare no conflicts of interest.

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