Abstract—This paper proposes a new design of ultra-thin and conformal SSPP based ultra wide band (UWB) low pass filter (LPF) employing the theory of spoof surface plasmon polaritons (SSPPs). The structure is made up of microstrip line corrugated with rectangular grooves which are loaded with equilateral triangle on both sides of the substrate. The thickness of the conformal SSPP filter is very small of the order of few micrometer and hence referred as nearly zero thickness metal strips resulting in a strong confinement over a wide frequency range. It has been identified that the designed filter has an UWB performance and its cut-off frequency can be easily controlled by changing the depth of the groove and spacing of the corrugations. The simulated results show a -10 dB bandwidth from 0 GHz to 11.96 GHz with a rejection level of 65 dB at 13.6 GHz. The proposed conformal UWB LPF can be extensively used in radio stripe networks for next generation beyond 5G applications.

Index Terms—Conformal spoof surface plasmon polaritons, UWB low-pass filter, Radio Stripe Network

I. INTRODUCTION

In approximately every 10 years, there is a new generation of cellular communications. With 5G already deployed in several parts of the world, researchers across the world have already started intense research works for beyond 5G (B5G) technologies. Massive MIMO (mMIMO) is already employed in 5G and it has been envisioned that cell-free massive MIMO (CF-mMIMO) utilizing the radio stripe network (RSN) architecture (see Fig. 6 and Fig. 7 of [1], Fig. 1 of [2]), is a strong proponent for B5G communications.

Owing to this, there is a need to create conformal circuits which can be rolled out on the facades of buildings, ceilings, side walls, etc. Filters are one of the major components of any communication circuits. In 2004, Pendry et al. introduced spoof surface plasmon polariton (SSPP) [3] where the surface waves are supported at microwave frequencies by etching sub-wavelength holes or grooves on the metal surfaces periodically and reported that the design parameters can be changed to alter the cut-off frequency and dispersion characteristics. Since then, many such SSPP structures have been proposed with very high field confinements [4], [5]. Conformal SSPPs are the surface EM waves that can travel long distances on ultra-thin and flexible films in a broad frequency range from microwave to mid-infrared [6]. These kind of waves can easily propagate on curved surfaces with a very low radiation loss. A nearly-zero thickness of metal impressed on flexible and ultra-thin dielectric films is employed for such conformal SSPPs.

In this article, an ultra-thin ultra wideband (UWB) low pass filter (LPF) for RSN applications will be designed.

Fig. 1. (a) Proposed unit cell structure, (b) Dispersion curve of unit cell.

This filter is conformal due to the flexible copper-clad laminate (FCCL) used [6], hence it is suitable for RSN. The LPF works on the principle of SSPPs which is devoid of any ground plane.

II. DESIGN OF UNIT CELL AND DISPERSION CURVE OF SPOOF SPP

A. Design of proposed unit cell

The diagram of the proposed unit cell is shown in Fig. 1(a). The geometric parameters are width of the transmission line w, depth of the rectangular groove h, gap d, side of equilateral triangle/width of the groove a and period of groove p. The structure has been designed on polyimide substrate with dielectric constant of 3.65, height of 508 µm, loss tangent of 0.0027, metal thickness of 18 µm and copper is used as metal with conductivity $5.8 \times 10^7$ S/m. The physical dimensions of the unit cell
considered here are \( h=1 \text{mm}, w=2 \text{mm}, d=4 \text{mm}, a=1 \text{mm} \) and \( p=5 \text{mm} \).

To investigate the SSPP performance, the dispersion behavior of the corrugated metallic grooves having mirror symmetry on the dielectric substrate is studied. Fig. 1(b) shows the dispersion relation of the proposed SSPP unit cell and is plotted using Eigen mode solver of CST Microwave Studio. Red and black lines indicate the propagation wave vector of the SSPP mode and the microstrip line respectively. The dispersion of SSPP approaches to an asymptotic frequency at 10.7 GHz.

**B. Conversion of QTEM mode to SSPP mode**

It can be noticed from Fig. 1(b) that the wave vector of SSPP is greatly misaligned with that of the light line which may result in very bad transmission. So an efficient conversion from microstrip’s Quasi TEM to SSPP mode is necessary. Therefore a transformation structure has been designed for the conversion and is shown in Fig. 2(a). The groove height is increased gradually from \( h_0=0 \text{mm} \) to \( h_7=0.875 \text{mm} \) with equal step size of 0.125 mm. The dispersion characteristics of the conversion is shown in Fig. 2(b). It can be observed that as the groove height decreases, the wave vector of SSPP approaches the light line and its momentum gets matched to momentum of light line. The relation between the dispersion characteristic and structural parameters is given as [7]

\[
\beta^2 = k_0^2 \left[ 1 + \frac{d^2}{p^2} \tan^2(k_0h) \right]
\]  

where \( \beta \) is the propagation constant of the SSPP mode and \( k_0 \) is the propagation constant of the wave in free space. It can be inferred from (1) that the wave vector can be modified by changing \( d, p \) or \( h \) and accordingly the cut-off frequency also changes. Fig. 2(c) indicates the dispersion behavior of the unit cell by changing \( d \) and \( w \) for two different values and Fig. 2(d) indicates the dispersion behavior of the SSPP unit cell by changing \( h, w \) and \( d \). It can be clearly seen that the plasma frequency can be effectively controlled by altering its geometrical parameters.

III. DESIGN OF LOW PASS FILTER

Fig. 3 depicts the geometry of the proposed SSPP based low pass filter (top view). The corrugations are spaced at a regular intervals of \( d \). The metal corrugated strip is placed symmetrically on both sides of the substrate. The depth of grooves decreases towards source and load from the center in order to achieve momentum and impedance matching. Fig. 4 shows the side view of the filter.

IV. RESULTS AND DISCUSSIONS

The simulated S-parameters of the designed filter are shown in Fig. 5. The frequency response has its cut-off frequency at 12.06 GHz and has a rejection level of 65 dB at 13.6 GHz and the -10 dB bandwidth ranges from 0 GHz to 11.96 GHz showing a UWB filtering. The insertion loss (IL) is less than 2 dB and return loss (RL) is more than 15 dB. The structure is again reproduced by changing its parameter values and the responses are shown in Fig. 6. The height of the groove and width
of the line are changed from 1mm to 3mm and 1mm to 2mm respectively and the corresponding S-parameters plots are shown in Fig. 6(a) and 6(b). It can be noticed that as the height decreases, the bandwidth increases at the expense of rejection level and the cut-off frequency can go up to 14 GHz. Fig. 6(c) to 6(f) shows the simulated results of the structure by changing w(1mm-3mm) and d(1mm, 3mm) for h=1mm and 2mm respectively. It has been observed that as width increases, bandwidth increases and increase in spacing results in decrease in bandwidth and rejection slope. The resonant frequencies are obtained by the strong interaction of plasma electrons at the metal dielectric boundary. These frequencies can be increased by incorporating more resonators into the design. Fig. 7 shows the group delay of the filter which has flat response and it is approximately 0.7 ns within the passband. Our proposed LPF is compared with the state-of-the-art in table I. It can be inferred that our conformal LPF is the only filter which is compatible with the RSN for B5G applications. Besides, our LPF is ultra-thin and has the smallest volume. Our LPF also has comparatively better filter’s performance than the existing filters.

V. CONCLUSION

A new structure employing triangular shapes on rectangular corrugated grooves along the microstrip line has been realized and SSPP based LPF has been designed. The filter is simulated on an ultra-thin substrate and an UWB filtering response has been observed with a -10 dB bandwidth from 0 GHz to 11.96 GHz. The IL and RL are <2 dB and >15 dB respectively within the passband of LPF. It can be observed that by carefully choosing the geometry, one can achieve a very good performance. This work can have its potential applications in RSN of B5G technology and RF transceivers composed of SSPP structures.

REFERENCES

<table>
<thead>
<tr>
<th>References</th>
<th>RL (dB)</th>
<th>IL (dB)</th>
<th>-10 dB BW (GHz)</th>
<th>Stopband rejection</th>
<th>Volume ($\lambda_g \times \lambda_g \times \lambda_g$)</th>
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<tr>
<td>[8]</td>
<td>&gt;10</td>
<td>&lt;4</td>
<td>0 - 7.3</td>
<td>44 dB @ 7.5 GHz</td>
<td>10.4×1.6×0.08</td>
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<td>&gt;10</td>
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<td>&gt;15</td>
<td>&lt;2</td>
<td>0 - 11.96</td>
<td>65 dB @ 13.6 GHz</td>
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