240 GHz meta-surface band pass filter and lens integration in 6G telecommunication systems

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Abstract
240 GHz operated meta-surface band pass filter consisting of split-ring resonator (SRR) matrix was simulated and measured as single and second order modes. The filter was integrated with hemispherical and Luneburg type of antenna lenses. The SRR meta-material filter was recommended component for 6G telecommunication applications characterizing measured values of 80 GHz bandwidth, low insertion loss (−0.75 dB) and good attenuation (−8 dB) characteristics close to the band pass region, and the filters can be cascaded to enhance its filtering characteristics.

KEYWORDS
lenses, microwave antenna arrays, resonator filters

1 | INTRODUCTION

Beyond-5G and 6G telecommunication radio systems are setting a goal of 1 Tbps over-the-air throughput for mobile devices. High spectral efficiency (bit/s/Hz) applied together with sub-THz frequency support wide enough bandwidths for the information signal. In the 4G wireless system typical information bandwidth is about 1 GHz, in the 5G system the bandwidth is 10 GHz and in the 6G system it could be 100 GHz. Digital and optical modulation processing together with THz radio front-ends are optional approaches for point-to-point or point-to-multipoint communications. THz range transmitter’s linearity, bandwidth and output power as well as receiver’s bandwidth, noise and linearity are key factors for transceivers design. THz frequencies suffer high path loss in the radio channel and low output power at the transmitter and requires the use of high-gain antennas with gains of 25 to 40 dBi depending on the application.

In the IEEE 802.15.3d2017 standard key characteristics of the amendment defining the physical layer in the frequency range 252.72 to 321.84 GHz are eight different channel bandwidths ranging from 2.16 to 69.12 GHz. Local oscillator in the mixer-type of transceiver architectures provides lot of spurious interfering signals that might be attenuated by certain filter structures. One option to improve the signal-to-noise ratio is to utilize band pass filters at intermediate frequency on the chip or circuit board. Another point of view is to use discrete filters on chip at sub-THz frequency. Furthermore, meta-material kind of structures located on top of the antenna, that is, on the radiated beam might be option for the filtering purposes and this is experimentally tested in this letter. The research questions are: has meta-surface filter realistic pass/rejection attenuation properties, enough bandwidth and is it possible to be used for incident waves arriving with different angles, and can it be integrated as a part of lens structures.

In this study, the meta-material filter structure consisting of periodic unit cells of double split-ring-resonators and composed of two concentric metallic rings with opposite splits as presented in Reference 5. Used split-ring resonator (SRR) element is coupled to a magnetic field component oscillating in the axial direction and the ring establishes a current flow composing a magnetic dipole parallel or antiparallel to the magnetic field. The SRR’s inductance and capacitance are equivalent to an LC resonant circuit, causing a strong magnetic response at its resonance. The inner concentric ring contributes to the net capacitance of the double SRR and thus lowers the resonance frequency. Hence, this ring boosts up the ratio between the operating wavelength and lattice constant, making the SRRs appear more homogeneous to the electromagnetic excitation. Moreover, this kind
of meta-material filters can be cascaded to form second order filter characteristics.\textsuperscript{6,7} Flexible wide bandwidth meta-surface filters were studied in Reference 8. SRR filters can be also integrated on waveguides.\textsuperscript{9} A band pass filter operated on the range of 1 to 2 THz and built by periodic circular dots stacked on several layers was presented by simulations in Reference 10 and experimentally in Reference 11. A complementary split-ring resonator to realize band pass characteristics at 310 GHz and with a spurious band rejection ratio over 50 dB at 1.28 THz.\textsuperscript{12} In addition, the technique can be applied at millimeter wave frequencies, for example, 10 GHz in Reference 13.

The electromagnetic behavior of single SRR element is presented in Figure 1. Vertically aligned electric E-field plane wave propagation (Figure 1A) is perpendicular to the split of SRR and horizontally aligned magnetic H-field (Figure 1B) couples effectively on parallel ring conductors at its operation frequency 240 GHz. A filter structure under measurements is presented in Figure 2A and filter combined with hemispherical lens in Figure 2B.

The array of SRR unit cells is presented as transmission line model equipped with the equivalent circuit model in Figure 3. The outer conductive ring of SRR\textsubscript{1} induces inductance L\textsubscript{1} and the gap is presented by the capacitance C\textsubscript{1}, as well as the inner ring fop, C\textsubscript{p} and R\textsubscript{p}, respectively. Other SRR\textsubscript{2-n} resonators in the array are presented in parallel to SRR\textsubscript{1} as \((2 - n)\) — multipliers that are coupled via L\textsubscript{c} and C\textsubscript{c} equivalent components in relation to the periodic dimensions of SRR array. Thus the filter of two SRR arrays is conducted by connecting certain transmission line model to the corresponding model that presents layer number two by using coupling factor that is related on the electromagnetic distance of particular layers.

### 2 MEASUREMENTS

Meta-material filter structures were fabricated on Rogers Duroid low loss circuit board (thickness 50 μm) with copper conductors (thickness 17 μm). Wide band THz-range measurements were carried out with Terapulse 4000 system and 9 mm of diameter plane wave and fabricated 30 mm of diameter of SRR matrixes (period 0.8 mm). At first, the angle of incident wave in terms of the filter surface was varied in order to find out the refraction effect of the wave propagation toward the meta-surface. Realistic angles in most wireless use cases are ±35°. Measured transmittance response of the filter is presented in Figure 4 in terms of varied angle of incidence 0, 15 and 35° that are all realistic scenarios in the 6G antenna applications. Measurements results of 0° tilt performed 85% (0.75 dB) transmittance, 15° tilt 82% transmittance and 35° tilt 74% transmittance at the 240 GHz of center frequency of the filter’s pass band. The bandwidth of the meta-material filter is about 80 GHz at 75% transmittance level.

Since out-of-band attenuation of SRR filter structures is not very high, they are normally cascaded to improve the filter characteristics. As can be seen in Figure 5 measured pass-band transmittance was 85% (−0.75 dB) for the first order filter, 66% (−1.8 dB) for second order filters with 250 μm gap, and 60% for second order filters with 1 mm gap between cascaded SRR matrixes. The reject band attenuations were 30%, 13% and 9% at 800 GHz respectively. The filter attenuation next to the passband at 400 GHz is at the highest 15% (−8 dB) of transmittance for the first order filter and 1% to 2% (−18 dB) for the second order filters.

The SRR filter can be integrated on the lens surface on several ways, on the straight or curved surfaces as presented in Figure 5. Hemispherical lens antenna (Figure 6A) is commonly known component for sub-THz range beam steering.

![FIGURE 1 Simulated E- and H-field responses of the double split-ring resonators at 240 GHz frequency. A, Vertically polarized E-field coupled on double split-ring resonator. B, Horizontally polarized H-field coupling on double split-ring resonator [Color figure can be viewed at wileyonlinelibrary.com]](image-url)
antenna applications. Luneburg lens (Figure 6B) is less used but feasible option for beam steering antenna applications. There are other combinations for filter locations, but presented three options were measured with the first order SRR filter in this study. Measurements were carried out by plane waves and antenna as a point source might result different outputs when SRR filter was located in different places. Lens materials were low permittivity organic composites.

Measured transmittance response of hemispherical lens with SRR filter is presented in Figure 7. Due to the energy focusing characteristics of lens structure the transmittance can achieve above 100% values in certain frequencies. Since the lens system was not focused in this certain measurements the results exhibited almost similar 85% transmittance for
lens and filter at 240 GHz. Together the lens and filter on the straight surface performed 65% transmittance, and 50% transmittance when the filter was on the curved surface. The transmittance response of Luneburg lens with SRR filter is presented in Figure 8. Without SRR filter the lens exhibited 30% transmittance and with SRR filter 23% transmittance. Again, unfocused measurement system scattered the beam, but the relative transmittance results shows that the filtered transmittance response is reasonable for further studies in the case.

Measured insertion loss characteristics of one layer filter at 240 GHz was $-0.75$ dB on the passband, with two layers the insertion loss characteristics of the filter was $-1.8$ dB and the rejection attenuation at 400 GHz was $-18$ dB. In corresponding filter results in Reference 12 the insertion loss value was $-1.8$ dB at 310 GHz and the rejection attenuation of $-20$ dB that results are almost similar than presented in this paper. However, our results were achieved with polymer substrate and copper conductor whereas they were compared to the filter built on sapphire material. The bandwidth of the SRR filter was 80 GHz being in relation 33% of the center frequency. It is close to the results in, but in the relative bandwidth was 22%. In previous papers the filter characteristics were presented in conventional ways, and features such as the operation for plane waves propagated in non-perpendicular direction were not considered. In addition the utilization of the filter together with lens structure is the novelty of the results enabling new ways to improve the radio system characteristics.

3 | CONCLUSION

The SRR meta-material filter was measured to be feasible component for 6G telecommunication applications. It
performed 80 GHz bandwidth, low insertion loss (−0.75 dB) and sufficient attenuation characteristics (−8 dB) close to the band pass region, and the SRR filters can be cascaded to enhance its filtering characteristics. The SRR filter can be integrated on the part of the lens antenna on either hemispherical or Luneburg structures.

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