Microwave filters based on novel dielectric split-ring resonators with high unloaded quality factors

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Abstract: Here, the authors present a new type of split-ring resonator (SRR) constructed from high dielectric constant material. Compared to conventional metal SRRs, such resonators have significantly higher unloaded quality factor ($Q_u$). A new class of microwave filter is presented using the dielectric SRR. Two examples of different filter configurations are investigated, and the measured results show excellent performance. Good agreement between measurements and simulations has been achieved.

1 Introduction

Filters formed of resonators with high unloaded quality factor ($Q_u$) are in demand for applications with stringent requirements on insertion loss, this includes satellite systems and wireless base stations [1–4] as well as many others. Dielectric resonators (DRs) are a popular choice for such applications [1–8]. Another common high $Q_u$ resonator is the metal or less common dielectric combline resonator, the latter has a $Q_u$ as high as DRs ($\varepsilon \tau = 10,000$ at S band and $\varepsilon \tau = 36$) [1, 9]. The electromagnetic field distributions and filter configuration for this dielectric combline is approximately the same as the conventional metal combline resonator, provided the dielectric constant is high [9–12].

Another type of resonator is the metal split-ring resonator (SRR) with $Q_u$ of $\sim 4000$ at S band manufactured with copper material [13–15]. This resonator is a hollow cylindrical ring with a longitudinal gap as shown in Fig. 1. Cavity filters based on metal-SRR are rarely reported [13, 14], but the metal-SRRs used more with the microwave sensors [16–21].

This paper investigates an SRR but with the metal replaced by a high permittivity dielectric. Such dielectric-SRRs have similar electromagnetic field distributions as the metal-SRR, but importantly, they have a higher $Q_u$ if made of a low-loss dielectric material. The higher $Q_u$ is due to the removal of the conduction current on the surface of the metal-SSR where most of the losses conventionally occur. As these ohmic losses are removed, the main contribution to the loss in the dielectric-SRR is loss tangent of the dielectric material forming the resonator [9, 22].

The $Q_u$ of the dielectric-SRR can be even higher than the $Q_u$ of DRs with the same $\varepsilon \tau$ and loss tangent. This is because with DRs, most of the energy is stored inside the DR [1, 22] which presents losses due to the loss tangent of dielectric material. In the case of dielectric-SRR, most of the energy is stored outside the dielectric material which reduces the effect of the loss tangent.

This paper looks at filters where the dielectric-SSRs are all in the same plane, alternatives have been investigated for metal-SRRs where they are placed on the top of each other in a cylindrical housing [13, 14]. The advantage of a planer configuration is it can easily achieve only electric or magnetic coupling between two adjacent resonators. Here, full-wave simulation analysis software (CST [23]) and the methodology of coupled resonator circuits [24] have been used to design new class of filter with examples of two high $Q_u$ filters based on the novel dielectric-SRRs.

2 Dielectric-SRR

The dielectric-SRR and metal-SRR have been modelled with the same dimensions as shown in Fig. 2a. Each is mounted on Teflon holder and in a copper enclosure, as shown in Fig. 2b. The fundamental mode field distributions have been simulated using an Eigenmode solver, and the results are shown in Fig. 3. As expected, most electric field is in the gap and the magnetic field peaks at the opposite side of the loop in both metal and dielectric SSRs. The fields are not high inside the dielectric material of the dielectric-SRR.

The dielectric and metal SSR have also been made, and the measurements together with the simulation results and are summarised in Table 1 which include details of the loss tangent for the high dielectric constant materials. It can be seen in Table 1 that the dielectric-SRR has a $Q_u$ around three times higher than that of metal-SRR in exactly the same configuration. Note the metal-SSR has a slightly lower frequency than the dielectric-SSR (2.3 GHz) then the $Q_u$ changes to 6200 still almost three times lower than the dielectric-SRR.

The $Q_u$ of the dielectric-SRR shown in Fig. 2 is now compared with $Q_u$ of the disk/cylindrical DR at fundamental resonance frequency of 2.3 GHz with the same $\varepsilon \tau$ and loss tangent. The DR model is shown in Fig. 4, with the ratio of $W/2R = 0.4$ to achieve the best $Q_u$ for the fundamental mode [1]. It is mounted on a Teflon holder and in a copper enclosure of 30 mm diameter and 50 mm height. Table 2 shows the CST Eigenmode simulation results for comparison between the now named dielectric-SRR1 and the DR1.

The comparison in Table 2 shows that for this particular configuration, the $Q_u$ of the dielectric-SRR1 is 50% higher than the $Q_u$ of DR1, but the radius of the dielectric-SRR1 is about twice that.
of the radius of DR1. It is the high \( Q_u \) which is of interest here and the fact that they are slightly larger than DR is of less importance.

There are other advantages of the SRR not used in the filters in this paper, this includes the ability to produce tuneable coupling by just rotation of the resonators [25] and the electromagnetic field distributions are very useful for the microwave sensors [16–21].

The dielectric constant \( \varepsilon_r \) of the material making the SSRs and DRs influences the amount of stored energy inside resonators. For instance, dielectric material of \( \varepsilon_r = 97 \) stores more energy inside the resonator than the case when \( \varepsilon_r = 36 \) [1, 6]. For this reason, the comparison between dielectric-SRR1 and DR1 has been repeated with the same enclosure and both resonators having the commonly used \( \varepsilon_r = 36 \). This is shown in Table 3. The Eigenmode CST simulation results in Table 3 have revealed the dielectric-SRR2 has a \( Q_u \) higher than DR2 by 30%. This percentage increase is less than the percentage increase from the comparison in Table 2, but is still significant. Again the dielectric-SRR2 has radius about twice the radius of DR2.

The dielectric-SSR configuration in Fig. 2 has been used to find the effects of dimensions on the fundamental mode frequency with the results shown in Fig. 5. These were all simulated with \( \varepsilon_r = 97 \).

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Table 1. \( Q_u \) comparison for dielectric-SRR and metal-SRR. Both resonators have same dimensions as in Fig. 2.

|                  | Dielectric-SRR Titania, \( \varepsilon_r = 97 \) | Metal-SRR copper \( \sigma = 5.813 \times 10^7 \) |
|------------------|--------------------------------------------------|--------------------------------------------------|
|                  | Simulated | Meas. | Simulated | Meas. |
| \( f, \text{GHz} \) | 2.3       | 2.29  | 1.66      | 1.68  |
| \( Q_c \) cavity | 122,510   | —     | 124,010   | —     |
| \( Q_u \) resonator | —        | 7,176 | —         | —     |
| \( Q_u \) holder | 315,080   | —     | 108,810   | —     |
| \( Q_u \) resonator | 24,502   | —     | —         | —     |
| \( Q_u \) | 19,176    | 17,021| 6,732     | 4,630 |

\( Q_c \), conductive quality factor; \( Q_u \), dielectric quality factor.

Table 2. Eigenmode CST simulation results for comparison between dielectric-SRR1 and DR1.

|                  | Dielectric-SRR1 | DR1 |
|------------------|-----------------|-----|
| \( f, \text{GHz} \) | 2.3             | 2.3  |
| \( Q_c \)         | 122,510         | 112,890 |
| \( Q_d \)         | 22,734          | 14,030 |
| \( Q_u \)         | 19,176          | 12,478 |

Table 3. Eigenmode CST simulation results for comparison between dielectric-SRR2 and DR2.

|                  | Dielectric-SRR2 | DR2 |
|------------------|-----------------|-----|
| \( f, \text{GHz} \) | 4.5             | 4.5  |
| \( Q_c \)         | 61,696          | 116,810 |
| \( Q_d \)         | 15,748          | 10,228 |
| \( Q_u \)         | 12,546          | 9,404 |

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Fig. 2 Configuration and dimensions in (mm) (a) Dielectric/metal-SRR: \( G = 3.5, R = 12.5, \) and \( W = 5 \), (b) Single resonator inside metal enclosure and mounted on PTFE holder

Fig. 3 Electromagnetic field distributions for dielectric-SRR of \( \varepsilon_r = 97 \) and metal-SRR. Section AA for top view and BB for side view, see Fig. 2b

Fig. 4 Configuration of disk DR. \( R \) is the radius and \( W \) is the height of DR
The gap of dielectric-SRR can be considered to represent a capacitor and loop represents inductor in the resonator equivalent circuit. Increasing the gap \( G \) (when the radius \( R \) and cross-section \( W \) are fixed) decreases the capacitance leading to an increase in the resonance frequency in Fig. 5a. The resonance frequency decreases when \( R \) increases due to an increase in the inductance loop length (Fig. 5b). The cross-section (kept square in this case) has more effect on the resonance frequency than \( G \) and \( R \) because increasing \( W \) will increase the capacitor surface area, leading to a decrease in the resonance frequency as shown in Fig. 5b.

The effects of dielectric-SRR dimensions, with \( \varepsilon_r = 97 \) and loss tangent of \( 7.2 \times 10^{-5} \), on the \( Q_u \) at the fundamental mode of 2.3 GHz are shown in Fig. 6. The same model shown in Fig. 2 is used in the Eigenmode simulation. The metal enclosure radius is kept to twice the dielectric-SRR radius \( R \) even when varying the \( R \) to decrease the enclosure effect on \( Q_u \). The conductive quality factors due to the walls, \( Q_c \), for all results in Fig. 6 are from 122,700 to 124,500, showing the walls have a minimal effect on the total \( Q_u \).

Here, \( W \) is varied with three different \( G \) values; with \( R \) tuned to fix the fundamental mode at 2.3 GHz. \( W \) has significant effect on \( Q_u \) due to increased gap area of the dielectric-SRR and the overall volume of resonator.

The mode separation between the fundamental mode of 2.3 GHz, and the first higher-order mode against dielectric-SRR dimensions, are shown in Fig. 7. The simulation results show the best mode separation can be achieved when \( W \) is from \( \sim 5 \) to 6 mm depending upon the value of \( G \).

### 3 Filter design

In order to design filters using the coupled resonator approach [24], we need to consider both the coupling to an external input/output transmission line and the coupling between two resonators. This is done in the following two sections followed by the full filter design.

#### 3.1 Coupling between resonators

The dielectric-SRRs (\( \varepsilon_r = 97 \)) with dimensions as shown in Fig. 2a and holder with \( \varepsilon_r = 2.1 \) with dimensions as shown in Fig. 2b have been chosen for the filter design. Firstly, we need to extract the coupling coefficients between two adjacent dielectric-SRRs. The published work about metal-SRR filters considered only a coaxial configuration [13, 14]. In this paper, novel dielectric-SRRs with a planer configuration have been examined. This introduces more flexibility in the design and can easily achieve electric coupling as well as magnetic and mixed coupling.

The coupling coefficients \( K_c \) are extracted by CST software for configuration when the angle \( \theta_1 \) of the first resonator and the angle \( \theta_2 \) of the second resonator are 90°, as shown in Fig. 8a. On the dimensional scales shown, the \( K_c \) values are small and nearly independent of the distance \( S \) between resonators. This is due to both electric and magnetic couplings providing partial cancellation and the coupling can be increased by having a metal wall between dielectric-SRRs. This is only from one side as shown by the inset in Fig. 8b. The \( K_c \) for configuration in Fig. 8b can be controlled by varying the metal wall dimensions between dielectric-SRRs as well as the distance \( S \).

Alternatively, significant, usable values for \( K_c \) can be obtained, without the metal wall, by changing the dielectric-SRRs angles \( (\theta_1 \text{ and } \theta_2) \) and varying distance \( S \) as shown in Fig. 9. A further
configuration is shown in Fig. 10, when the gaps of two adjacent dielectric-SRRs face each other with a wall coming down from the top of the cavity housing in this case. This configuration can easily achieve electric coupling with the negative $K_c$ values as given in Fig. 10. It should be noted there are many more possibilities for coupling the resonators, for example, as a function of the rotation angle $\theta$. However, only the coupling used in the filters have been discussed here.

### 3.2 Extraction of external quality factor

The coupling to the input and output, as defined through the external quality factor $Q_e$, for the dielectric-SRRs is extracted based on the method described in [24]. This coupling is achieved through a probe as shown in Fig. 11a. The model configuration and CST simulation results for $Q_e$ against different probe lengths ($L$) and heights ($H$) for probe moving from the centre of dielectric-SRR towards right are shown in Fig. 11b.

In addition, $Q_e$ is extracted when moving the feeding probe from the center of SRR towards its gap with $H=1$ mm.

### 3.3 Design of filters

The filters are designed by considering various combinations of resonators and their coupling. The design process involves selecting appropriate resonator configurations and adjusting the coupling coefficients to achieve the desired filter response.

### Conclusion

The proposed dielectric-SRR filters offer several advantages over traditional SRR filters, such as improved isolation and bandwidth. The flexibility in design allows for customization to meet specific application requirements.
3.3 Third-order filter

This filter is designed to have a Chebyshev response, with a centre frequency of 2.2 GHz, fractional bandwidth (FBW) of 5%, and return loss of 20 dB. The non-zero coupling coefficients of filter are calculated to be $M_{12} = M_{23} = 0.05$, and the external quality factor are $Q_{e1} = Q_{e2} = 17$ [24]. Fig. 12 shows the filter configuration as well as overall dimensions and the fabricated filter. Detailed dimensions of the resonators and holders can be found in Fig. 2.

The simulation and measurement results are shown in Fig. 13a. The $S_{21}$ response is not symmetrical; this is due to the appearance of a transmission zero. Simulation has shown this zero is attributed to the unwanted cross-coupling between the input and output coaxial cables. Such a transmission can be moved in frequency or suppressed by a more complex use of walls. However, this study is not part of this work. There is a small frequency shift in measured response, and this is due to small errors in fabrication. Note that there has been no tuning of the filter. Tuning screws are able to correct this small frequency shift; however, the agreement is good and therefore, we have not done the tuning. Results without tuning demonstrate more about the accurate construction and design than do tuned results.

The return loss is >20 dB which is an excellent result. The measured insertion loss is $\sim 0.3$ dB higher than simulated. From this measured insertion loss, the effective unloaded $Q$ of resonators can be calculated as 11,125 [24]. This can be compared with 19,176 in Table 2. So both the insertion loss and $Q_2$ tell us that there are additional unexpected losses. This can be attributed to (i) potential small errors in the assumed material parameters such as the loss tangent, (ii) the losses in the 3 cm semi-rigid cables connecting to the devices, (iii) losses in SMA connectors, (iv) manufacturing problems, particularly with the cables and earth connection to the outer cavity, and (v) the small effect of the return loss on the insertion loss. Some of these errors are small, some are difficult to quantify, but the expectation is that the additional loss is a combination.

The $S_{21}$ responses across a wider band are shown in Fig. 13b, the first higher spurious response occurs at 2.85 GHz, and is at a similar frequency to simulation results of the single dielectric-SRR and comparable with the spurious performance of DR filters [1].

3.4 Fourth-order filter with symmetric transmission zeros

This filter is designed to have a centre frequency of 2.3 GHz, FBW of 4%, and return loss of 20 dB. A cross-coupling is added between resonators R1 and R4 to provide a pair of transmission zeros at the frequencies of 2.227 and 2.374 GHz. The non-zero coupling coefficients are calculated as [24] $M_{12} = M_{24} = 0.033$, $M_{23} = 0.032$, and $M_{14} = -0.01$, and the external quality factor are $Q_{e1} = Q_{e2} = 24$. The configuration and filter dimensions as well as the fabricated filter are shown in Fig. 14, the dimensions of the resonator and holder as given in the previous section in Fig. 2.

The simulation and measurement results are shown in Fig. 15. Again this filter has an excellent return loss of >20 dB with a minimum insertion loss of only $\sim 0.3$ dB. The untuned filter has a small frequency shift which also moves the position of the transmission zeros slightly.

4 Conclusion

A new high $Q_0$ resonator has been described; it uses a high dielectric constant material to implement a dielectric-SRR, rather than the conventional metal-SRR. The novel dielectric-SRR has higher $Q_0$ than both the metal-SRR and the conventional disk DR.
microwave filter have been presented with third- and fourth-order examples based on the novel dielectric-SRRs and the method of a coupled resonator circuits. The measurement results of both filters have very good agreement with the simulation results and a very low insertion loss, of ~0.3 dB, has been achieved.

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6 References
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Fig. 14 Fourth-order dielectric-SRR filter configuration
(a) Top view, (b) Side view, R1, 2, and 3 indicate to resonators, (c) Fabricated filter. Unit: millimetre

Fig. 15 Measurement and simulation results of the fourth-order dielectric-SRR filter
The effect of dielectric-SRR dimensions on the $Q_d$ and mode separation has been described.

For filter design, the internal and external couplings for dielectric-SRRs have been extracted and studied. A new class of