Gradual cross polarization conversion of transmitted waves in near field coupled planar terahertz metamaterials

S. JAGAN MOHAN RAO, 1,4 RAKESH SARKAR, 1 GAGAN KUMAR, 1
AND DIBAKAR ROY CHOWDHURY 2,3

1Department of Physics, Indian Institute of Technology Guwahati, Guwahati, 781039, India
2Mahindra Ecole Centrale, Jeedimetla, Hyderabad, 500043, India
3dibakarrc@gmail.com
4suraboinajmr@gmail.com

Abstract: In this work, we examine gradual cross polarization conversion using two coupled circular split ring resonators (SRRs) in the terahertz (THz) frequency regime. In the proposed geometry, a metamolecule (unit cell) is comprised of two circular split ring resonators having a single split gap. One resonator is rotated with respect to the other from 0° to 180° in the steps of 15° and thereby, co- and cross-polarization components of the transmitted terahertz are investigated. The cross polarization component is observed to be maximum when resonator split gaps are orthogonal to each other; however, in the co-polarization resonance, a strong split is observed. Based upon the angle of rotation between the resonators, the study reveals that the cross polarization conversion can be tuned from minimum to maximum and then back to the minimum. We have employed a semi-analytical model to understand the polarization conversion arising from the coupling between the resonators and found that it corroborates numerical findings. The ability to control linear polarization conversions can be significant in the development of THz polarimetric devices.

© 2019 Optical Society of America under the terms of the OSA Open Access Publishing Agreement

1. Introduction

The field of terahertz has seen a rapid growth in last few years because of its significance in diversified applications such as imaging, sensing and communications. For most of these applications, not only efficient terahertz sources are required, but also very high-speed terahertz components and devices to control and manipulate the terahertz waves are essential. Those components include switches, modulators, polarization converters, antennae, sensors etc. [1,2]. Most of the natural materials do not respond to terahertz radiations, therefore it is important to explore alternate methods to make devices in terahertz domain. By utilizing the metamaterials (MMs) concept [3], efficient terahertz devices can be realized [4]. Metamaterials exhibit several fascinating features and applications including negative refractive index [5], invisibility clocking [6], perfect lens to overcome the diffraction limits [7] etc. Metamaterials research began with J. Pendry’s seminal 1999 paper on split ring resonators (SRRs) [8]. At the resonance frequency of metamaterials, a strong localization of electromagnetic energy takes place in the resonator which results enhancement of amplitude at the resonance frequency. The feature is important to several applications in the terahertz regime. Additionally, circular currents can be induced in the split ring resonators giving rise to an inductance in the designed resonators. The combination of capacitive and inductive nature of SRRs leads to strong inductive capacitive resonance, termed as fundamental resonance [9]. Several studies have been reported on THz transmission in two dimensional MMs using single SRR as the unit cell [9–13]. When two SRRs are brought sufficiently close to each other, they can couple strongly through magnetic and electric field lines gives rise to several interesting phenomena including mode hybridization effect, broadband
modulation, wave modulation, plasmon induced transparency (PIT) [14–17] etc. In this context broadly two types of SRRs are investigated, they are broad side coupled SRRs (BC-SRRs) [18] and edge coupled SRRs (EC-SRRs) [19–21]. In both the cases, the SRRs are placed orthogonal to each other in a metamaterial unit cell. Upon incidence of a linearly polarized light, one SRR is directly excited and it is termed as bright resonator, whereas the other resonator is excited indirectly through the bright resonator, hence called as dark resonator [22,23]. In case of MMs configuration, where both the SRR gaps are aligned parallel to incident electric field, the bright modes are excited simultaneously in both the resonators [24,25].

Polarization rotation is an important phenomena in many applications [26–34]. Generally polarization rotation is achieved by using conventional methods like prism rotators using total internal reflection principle and the wave retarders which alter the polarization of light based upon the principle of birefringence. Their performance is wavelength-specific and they have their own limitations. Therefore, more convenient and flexible approaches are desirable to fully manipulate the polarization state of an electromagnetic wave. Recently, near field coupled metamaterials exhibited great promise to realize polarization rotation [35–38]. Many schemes have been implemented to rotate the polarization state at THz frequencies using novel metamaterial configurations. Grady et al. have reported the rotation of linearly polarized light to its orthogonal state using ultrathin, broadband and highly efficient MM configuration [39]. Cong et al. studied the rotation of a linearly polarized broadband terahertz wave using tri-layer metasurfaces [40]. In another study, polarization conversion in reflection mode was accomplished using metamaterial unit cell composed of a metallic disk and split-ring resonator placed near to the ground plane and separated by a polyamide layer. This configuration can result in the rotation of a linearly polarized light by 90° with an extended operation bandwidth [41]. Wen et al. studied polarization rotation in reflection mode using three layers of planar structures on the top of a two-dimensional array of tilted coupled split rings (TCSRs) [42]. Xia et al. demonstrated a linear polarization converter composed of two metal layers and a dielectric spacer [43]. Chen et al. investigated the magnetic interactions of edge coupled twisted split ring resonator pairs as a function of their coupling strength to control the polarization conversion in both the transmission and reflection mode [35]. Very recently a linear polarization conversion of transmitted terahertz wave with double-layer meta-grating surfaces in transmission mode is also demonstrated [44]. Yang et al. studied broad band polarization conversion in reflection mode by using the hybrid metamaterial unit structure consisting of a split-ring metal pattern and a metal sheet separated by a dielectric resonator spacer [45]. So far, many works have been reported on linear polarization rotations using relatively simple and complex metamaterial geometries, however, polarization rotation at relatively small angles is overlooked. In this work, we have studied gradual control of linear polarization rotation with a simple planar metamaterials capable of working in the terahertz frequency regime.

In this work, we propose a metamaterial unit cell comprising of two near field coupled circular resonators on a silicon substrate with the ability to gradually rotate and control linearly polarized light. We study the polarization rotation in transmission mode using the designed MMs in the 0.2 THz to 0.8 THz frequency range. The terahertz transmissions of the coupled structures are studied by varying rotation angle of one resonator with respect to the other one. We examine the co- and cross-polarization transmission for different rotation angles of one resonator with respect to another resonator. In the first section, the design of MM geometry has been discussed along with the effect of rotation angle on the coupling of fundamental LC resonances. The numerical results are discussed in detail in the next section. Further, we discuss lumped-element RLC circuit model in order to validate the numerical results. Finally, the results are summarized in the conclusion section.
2. Metamaterial design and numerical simulation details

Design of THz metamaterial is very crucial in order to accomplish variable magnitude of the co- and cross-polarization responses. In our proposed metamaterial configuration, metamolecule (unit cell) is comprised of two circular split ring resonators (SRRs) and separation between two resonators is fixed at 1 $\mu$m throughout this study. A schematic of the proposed configuration is shown in Fig. 1. We have assumed silicon of thickness 50 $\mu$m as the substrate with a permittivity of $\epsilon = 11.9$ and negligible loss. Other dimensions of substrate are assumed to be, length x breadth = 100 $\mu$m x 60 $\mu$m. The unit cell is chosen to be much bigger in size compared to the resonators pair in order to avoid any inter metamolecular coupling. The circular SRRs as depicted in the Fig. 1(b) are 20 $\mu$m and 16 $\mu$m in outer and inner radius, respectively, and made of gold layer of 200 nm thickness. The capacitive gap (g) and line width (w) of both the resonators are taken to be, same i.e. 4 $\mu$m. The geometrical parameters are kept constant throughout the analysis. In Fig. 1(b), $\theta$ is the angle between the split gaps of left and right SRR and is changed from 0° to 180° during this study. We fix the right side resonator and rotate the left side resonator from 0° to 90° and further 90° to 180°, in an anticlockwise fashion at an interval of 15° and observed co-polarization as well as cross polarization transmissions corresponding to various relative orientations (Fig. 1). For our numerical study, we have employed commercially available numerical software, CST Microwave Studio and used tetrahedral meshing in order to accurately measure the response of geometry. We have used waveguide ports for the source and detector. In all simulations, plane wave excitation is used with normal incidence, containing modes linearly polarized in either x or y direction. Periodic boundary conditions are used to...
simulate an infinite two-dimensional periodic array, with unit cell and structural dimensions specified in Fig. 1(b). The transmission results are normalized w.r.t. the transmission from a bare substrate and plotted in Fig. 2. These plots represent transmissions, $T_{yy}$ and $T_{xy}$ that contain both y- and x-polarization components, respectively, excited by the incident field linearly polarized in y direction. In this study, the polarization of the incident THz beam is assumed to be along the split gap of the right resonator in order to excite the fundamental LC resonance. The split resonances result from the coupling of right side split ring resonators with the left side resonators through a combination of magnetic and electric flux because of edge coupling of the twisted circular resonators [23,46]. The amplitude transmission shows a resonance split and results in maximum polarization conversion (Fig. 2) due to a comparatively strong inductive coupling of the fundamental resonances of right and left circular resonators. The results of the terahertz transmission for both polarizations through inductively coupled THz metamaterial systems are discussed elaborately in the next section.

![Fig. 2](image_url)  
**Fig. 2.** Numerically simulated transmission of the metamaterials. (a) Co-polarization amplitude transmission for left SRR rotation from 0° to 180° (b) Cross-polarization amplitude transmission results for left SRR rotation from 0° to 180°.

3. Results and discussions

In order to examine the terahertz co and cross polarization transmission properties of the near field coupled metamaterial responses, we rotate the LHS SRR with respect to the RHS SRR in the anticlockwise direction. The results are shown in Fig. 2 and in Fig. 3. In Fig. 2(a), we plot the THz co-polarization transmission amplitude versus frequency and in Fig. 2(b), we plot the THz cross-polarization transmission amplitude versus frequency for 0°, 45°, 90°, 135°, and 180°. At $\theta = 0°$, transmission shows single resonance at 0.5246 THz with cross polarization amplitude almost zero. As the relative SRR rotation is changed through the rotation angle from 0° to 15°, 30°, 45°, 60°, 75°, and 90°, we observed the gradual decrease in co-polarization transmission amplitude accompanied by a gradual increase in cross-polarization transmission amplitude. For $\theta$ less than 45°, the single resonance appears nearly at 0.5246 THz in co-polarization transmission and beyond $\theta = 45°$ till 90°, resonance split appears in co-polarization transmission with the lower resonance appearing near 0.4802 THz and the higher resonance at 0.5276 THz (see Fig. 2(a)). At $\theta = 90°$, clear resonance split takes place with resonance dips at 0.4922 THz and 0.5222 THz in cross-polarization transmission. At this configuration maximum polarization conversion is achieved with conversion amplitude as 0.33 (see Fig. 2(b)). Further, LHS SRR is rotated with respect to RHS SRR from $\theta = 90°$ to 180°. For the range of $\theta = 90°$ till 120°, resonance split in co-polarization transmission amplitude exists with the lower resonance close to 0.4802 THz and higher frequency resonance close to 0.5276 THz. From $\theta = 135°$ to 180°, a single resonance dip
occur at 0.4802 THz in co-polarization transmission. With the change in rotation angle from $\theta = 90^\circ$ to $180^\circ$, a gradual increase in co-polarization transmission amplitude is observed along with a gradual decrease in cross-polarization transmission amplitude and finally at $\theta = 180^\circ$, linear polarization rotation conversion reaches to zero. Further the intrinsic resonance of the SRR is observed at 0.4964 THz (Fig. 3a). However, the split resonances are observed centering the intrinsic resonance. In order to understand the phenomenon behind the co and cross polarization transmissions elaborately, we have provided the qualitative analysis below. In our studied MMs, two circular split ring resonators are placed side by side to each other on silicon substrate. When the incident electric field is linearly polarized along the y-direction, the fundamental resonance mode of the right side SRR is always directly excited [9,12]. The incident electric field parallel to split gap creates circular current in right SRR with the accumulation of charges at the split gap (Fig. 5). With $\theta = 0^\circ$ bright mode in both the resonators are excited. However there is a strong inductive coupling changing the effective inductance of the resonators, therefore shifting the resonance from its intrinsic position (Fig. 2). As the LHS resonator rotates ($\theta$ increasing), the LHS resonator slowly moves from bright regime ($\theta = 0^\circ$) to dark regime ($\theta = 90^\circ$). In case of $\theta = 90^\circ$ the LHS is excited indirectly through the RHS bright resonator which is followed by inter resonator coupling to give rise to resonance mode splitting [23]. At this position the radiation of dark resonator is completely orthogonal to the incoming wave, hence we observe maximum magnitude of cross polarization. With further rotation ($\theta > 90^\circ$), the LHS resonator gradually comes out of dark mode regime to bright regime. In the process the orthogonal polarization conversion diminishes and finally at $\theta = 180^\circ$ both the resonators are excited directly through the incident electric field, hence no polarization conversion takes place. However the resonance dip appears at a different frequency than intrinsic case because of the effective inductance of the resonators. The induced circulating currents are in opposite direction resulting in different value of effective inductance.

![Fig. 3. Comprehensive numerical simulation transmission amplitudes for $\theta$ varying from 0° to 180°. (a) Contour plot for co polarization amplitude transmission for left SRR rotation from 0° to 180° (b) Contour plot for cross polarization amplitude transmission results for left SRR rotation from 0° to 180°.](image)

For an elaborate understanding of co and cross polarization amplitudes, comprehensive simulation results are shown through contour plot (Fig. 3). Figure 3(a) and (b) represents contour plots for co and cross polarization transmissions, respectively. In Fig. 4(a), rotation angle is plotted against the resonance frequencies for the co-polarization transmission amplitudes. Blue line represents fundamental resonance of the intrinsic resonator, whereas the red and green lines represent the lower and higher order resonance frequencies for the coupled resonators, respectively. Figure 4(b) depicts the polarization conversion amplitude with rotation angle of the LHS resonator. With an increase in the rotation angle, cross polarization amplitude
increases gradually till it reaches $90^\circ$ where the linear polarization conversion attains maximum value. With further increase in $\theta$, cross polarization decreases, and at $180^\circ$ rotation angle, the cross polarization conversion amplitude reaches to zero. From our study, it is evident that the cross polarization conversion can be tuned from zero to maximum depending upon the relative orientation of the resonators.

![Graphs showing rotation angle vs resonance frequency and cross polarization conversion amplitude](image)

**Fig. 4.** (a) Rotation angle vs resonance frequency plot for co polarization amplitude transmission. Left SRR rotation from $0^\circ$ to $180^\circ$ (b) Rotation angle vs cross polarization conversion amplitude plot. Left SRR rotation from $0^\circ$ to $180^\circ$.

We have further studied the electric field profiles and surface current profiles for $0^\circ$, $90^\circ$ and $180^\circ$ cases. The induced surface current and electric field distributions are shown in Fig. 5 at the resonance dips. At 0.5246 THz for $0^\circ$ case, the induced currents are in phase for both the resonators. This is the situation when both the resonators behave like the bright resonators. Electric field distribution depicts the bright mode excitation in both the resonators (Fig. 5(a) and (b)). Surface current and electric field profiles for $\theta = 90^\circ$ at lower and higher resonance modes are shown in Fig. 5(c), (d), (e) and (f), respectively. Figure 5(c) and (d) illustrates that the induced currents are out of phase whereas induced currents are in phase as revealed by Figs. 5(e) and (f). In Fig. 5(g) and (h), electric field distribution and surface current distribution are shown for $180^\circ$ situation. However, the nature of induced currents are different in two resonators.
Fig. 5. Simulated surface current and electric field profiles for 0°, 90°, and 180°. (a) & (b) represents electric field and surface current profiles for 0° at 0.5246 THz. (c) & (d) represents electric field and surface current profiles for 90° at lower resonance frequency 0.4802 THz. (e) & (f) represents electric field and surface current profiles for 90° at higher resonance frequency 0.5276 THz. (g) & (h) represents electric field and surface current profiles for 180° at resonance frequency 0.4766 THz.
Fig. 6. Schematic of the RLC circuit model. The electrical components $R_1, L_1, C_1$ represent the resistance, inductance, capacitance describing the fundamental LC resonance of the right meta-resonator and $R_2, L_2, C_2$ describe the resonance for the second left resonator. $I_1$ and $I_2$ represent the excited currents in right and left resonators respectively. The parameter $M$ is responsible for the coupling between the resonators.

4. Theoretical model

In order to validate the co and cross polarization transmission results obtained through coupled metamaterials, we have employed a semi-analytical RLC circuit approach (Fig. 6) [35,47]. This model has the ability to give us insight into the resonant co and cross polarization transmission behavior through the proposed coupled metamaterials system. In this semi-analytical approach, a single SRR is modeled with an equivalent RLC circuit which exhibits resonance at a specific frequency depending upon the shape and size of the split ring resonator. For our case, we assumed two RLC circuits with resistances, inductances and capacitances as $R_1, L_1, C_1$ and $R_2, L_2, C_2$ corresponding to the right and left resonators, respectively (Fig. 6). When incident electric field ($E_{\text{in}} = \frac{V}{g}$, where $V$ is voltage and $g$ is the split gap of SRR) is linearly polarized along $y$ direction, the fundamental resonance mode of only the right SRR is excited (because right SRR capacitive gap oriented along $y$ direction). This is considered as a primary loop where circulating current is $I_1$. The fundamental mode of left SRR can not be excited due to its different orientation. So, left SRR will be excited because of right SRR through near field inductive coupling and the coupling parameter is mutual inductance ($M$). This is called a secondary loop and circulating current is $I_2$. Using Kirchhoff's voltage law, we can write equations for primary loop and secondary loop as below

\begin{align}
[R_1 + j\omega L_1 + \frac{1}{j\omega C_1}][I_1] + j\omega M I_2 &= V \\
 j\omega M I_1 + [R_2 + j\omega L_2 + \frac{1}{j\omega C_2}][I_2] &= 0
\end{align}

Using Cramer's rule, if you solve $I_1$ and $I_2$

\begin{align}
I_1 &= \frac{V[R_2 + j\omega L_2 + \frac{1}{j\omega C_2}]}{[R_1 + j\omega L_1 + \frac{1}{j\omega C_1}][R_2 + j\omega L_2 + \frac{1}{j\omega C_2}] - \omega^2 M^2 j^2} \\
I_2 &= \frac{V j\omega M}{[R_1 + j\omega L_1 + \frac{1}{j\omega C_1}][R_2 + j\omega L_2 + \frac{1}{j\omega C_2}] - \omega^2 M^2 j^2}
\end{align}

Where $j$ is the imaginary unit and $\omega$ is the angular frequency of the incident electromagnetic waves. The induced electric dipoles are proportional to the charge accumulation at the split gaps, i.e. $P_{1,2}$ is proportional to $\int I_{1,2} dt$. From above analysis, we know $I_1$ is responsible for co-polarization and $I_2$ is responsible for cross polarization transmission. Now from $I_1$ and $I_2$, we can derive total impedance for co and cross polarization transmissions. We know $Z = \frac{V}{I}$,
then $Z_{co} = \frac{V}{I}$ and $Z_{cross} = \frac{V}{I}$ now we can write total impedance for co and cross polarization transmissions.

$$Z_{cross} = \frac{Z_1 Z_2 - (Z_m)^2}{Z_m}$$  \hspace{1cm} (5)

$$Z_{co} = \frac{Z_1 Z_2 - (Z_m)^2}{Z_2}$$  \hspace{1cm} (6)

where

$$Z_1 = R_1 + j\omega L_1 + \frac{1}{j\omega C_1}$$  \hspace{1cm} (7)

$$Z_2 = R_2 + j\omega L_2 + \frac{1}{j\omega C_2}$$  \hspace{1cm} (8)

$$Z_m = j\omega M$$  \hspace{1cm} (9)

Normalized transmission formula [12,48] for co and cross polarization is

$$t(\omega) = \frac{Z_{total}(Z_s + Z_0)}{Z_s (Z_{total} + Z_0) + (Z_{total} Z_0)}$$  \hspace{1cm} (10)

Where, $Z_s$ (impedance of Si substrate) = 103 $\Omega$ and $Z_0$ (impedance of free space) = 377 $\Omega$.

We have used equation 10 to get co and cross polarization transmission results. For co-polarization transmission results, we have substituted equation 6 in place of $Z_{tot}$ into equation 10 and varies R, L, C and M values. At particular values of R, L, C and M, we calculated co-polarization transmission plots (See Table 1 for R, L, C and M values). The results of amplitude transmission through RLC-circuit model for co-polarization are shown in Fig. 7(a). The corresponding values of coupling parameter M are given in table-1. We observe increase in M value with an increase in rotation angle of left SRR from 60° to 90° and from 90° to 120° M value got decreased. The calculated amplitude transmission is found in good agreement with the numerical simulations. Next, for cross-polarization transmission results, equation 5 is substituted in place of $Z_{tot}$ in equation 10. Using final transmission (equation 10) expression and at particular R, L, C and M values (See Table 2), we calculated the cross polarization transmissions. These results too match well with our numerical simulations (shown in Fig. 7(b)). Mutual inductance (M) values (Table 1 and Table 2) for both the co and cross polarizations cases show a certain trend i.e. till 90° it increases and beyond 90° till 120° it decreases gradually. From this, we can conclude that at 90° mutual inductance attains highest value. Since mutual inductance M represents coupling strength, this indicates that at 90°, the resonators are maximally coupled through mutual inductance. Beyond this point, if left SRR is rotated in anti-clockwise fashion with respect to the right SRR, the coupling strength decreases as can be confirmed from mutual inductance values.

<table>
<thead>
<tr>
<th>Rotation angle (θ)</th>
<th>$R_1$ (ohm)</th>
<th>$L_1$ (pH)</th>
<th>$C_1$ (fF)</th>
<th>$R_2$ (ohm)</th>
<th>$L_2$ (pH)</th>
<th>$C_2$ (fF)</th>
<th>$M$ (pH)</th>
</tr>
</thead>
<tbody>
<tr>
<td>60°</td>
<td>35</td>
<td>245</td>
<td>0.38</td>
<td>34</td>
<td>165</td>
<td>0.64</td>
<td>12</td>
</tr>
<tr>
<td>75°</td>
<td>52</td>
<td>245</td>
<td>0.4</td>
<td>32</td>
<td>165</td>
<td>0.63</td>
<td>19</td>
</tr>
<tr>
<td>90°</td>
<td>52</td>
<td>282</td>
<td>0.38</td>
<td>32</td>
<td>200</td>
<td>0.5</td>
<td>20</td>
</tr>
<tr>
<td>105°</td>
<td>40</td>
<td>342</td>
<td>0.32</td>
<td>32</td>
<td>194</td>
<td>0.5</td>
<td>14</td>
</tr>
<tr>
<td>120°</td>
<td>35</td>
<td>282</td>
<td>0.4</td>
<td>32</td>
<td>180</td>
<td>0.2</td>
<td>12</td>
</tr>
</tbody>
</table>
Fig. 7. Terahertz amplitude transmission through the coupled resonators in planar THz metamaterials obtained from RLC circuit model for various rotations of left split ring resonator w.r.t right SRR. The results affirm numerical observations. (a) Co-polarization transmission. (b) Cross-Polarization transmission.

<table>
<thead>
<tr>
<th>Rotation angle ($\theta$)</th>
<th>$R_1$ (ohm)</th>
<th>$L_1$ (pH)</th>
<th>$C_1$ (fF)</th>
<th>$R_2$ (ohm)</th>
<th>$L_2$ (pH)</th>
<th>$C_2$ (fF)</th>
<th>$M$ (pH)</th>
</tr>
</thead>
<tbody>
<tr>
<td>60°</td>
<td>250</td>
<td>145</td>
<td>0.4</td>
<td>312</td>
<td>125</td>
<td>0.2</td>
<td>179</td>
</tr>
<tr>
<td>75°</td>
<td>250</td>
<td>125</td>
<td>0.4</td>
<td>312</td>
<td>125</td>
<td>0.2</td>
<td>205</td>
</tr>
<tr>
<td>90°</td>
<td>250</td>
<td>141</td>
<td>0.4</td>
<td>312</td>
<td>125</td>
<td>0.2</td>
<td>224</td>
</tr>
<tr>
<td>105°</td>
<td>250</td>
<td>156</td>
<td>0.4</td>
<td>312</td>
<td>125</td>
<td>0.22</td>
<td>220</td>
</tr>
<tr>
<td>120°</td>
<td>250</td>
<td>205</td>
<td>0.4</td>
<td>312</td>
<td>125</td>
<td>0.2</td>
<td>210</td>
</tr>
</tbody>
</table>

5. Conclusion

To summarize, we have presented a gradual linear polarization convertor with a double split ring resonator based metamaterials system operating in the terahertz regime without changing the metamolecule unit cell size. We have tuned cross polarization and co polarization transmissions by changing the relative rotation angle of one resonator with respect to the other from 0° to 180°. We have demonstrated that the cross polarization transmission amplitude gradually changes from zero to maximum and then back to zero. At the same time, the co-polarization transmission amplitude varies from single resonance dip to split resonance dips and then back to single resonance dip. With the rotation angles at 90°, the maximum cross polarization conversion is achieved. When the left side circular resonator split gap rotation angles are close to $\theta = 0^\circ$ or $180^\circ$, minimum cross polarization conversion is achieved along with a single resonance in co-polarization transmission because of the absence of mode hybridization where resonators behave close to the intrinsic resonators. We have monitored electric field and surface current profiles to confirm our observations. Further, an RCL theoretical model is employed to validate the coupling mechanisms in detail. We considered the circular SRRs as lumped element RLC resonant circuits and calculated the induced currents within the circular SRR loops. Finally, we calculated the co and cross polarization transmissions. Our theoretical outcomes are in good agreement with our numerical results. The present work for our studied near field coupled metamaterials boosts the understanding of near field resonator coupling within the composite metamolecules, which can lead to realization of polarization manipulation devices in terahertz regime.
Funding

Board of Research in Nuclear Sciences (BRNS) (34/20/17/2015/BRNS); Science and Engineering Research Board (SERB) (EMR/2015/001339); Ministry of Human Resource Development (MHRD).

Acknowledgments

GK gratefully acknowledges the financial support from the Board of Research in Nuclear Sciences (BRNS), India (34/20/17/2015/BRNS). DRC gratefully acknowledges the financial support from the SERB, Department of Science and Technology, India (EMR/2015/001339). SJM Rao and R Sarkar would like to acknowledge the financial support from the Ministry of Human Resource Development, Government of India for a research fellowship.

References