Spectrally tunable linear polarization rotation using stacked metallic metamaterials

Xavier Romain, Fadi I Baida and Philippe Boyer

Département Optique, Institut FEMTO-ST UMR 6174, Université Bourgogne Franche-Comté–CNRS, F-25030 Besançon, France
E-mail: xavier.romain@femto-st.fr

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Abstract
We make a theoretical study of the transmission properties of a stack of metallic metamaterials and show that it is capable of achieving a perfect transmission selectively exhibiting broadband ($Q < 10$) or extremely narrowband ($Q > 10^5$) polarization rotation. We especially highlight how the arrangement of the stacked structure, as well as the metamaterial unit cell geometry, has a large influence on transmission in the spectral domain. For this purpose, we use an extended analytical Jones formalism that allows us to obtain a rigorous and analytical expression of the transmission. Such versatile structures could find potential applications in polarimetry or in the control of light polarization for THz waves.

Keywords: metamaterials, polarization rotation, spectral tunability

(Some figures may appear in colour only in the online journal)

1. Introduction

Much effort has been made to gain a physical and theoretical understanding of enhanced transmission through periodically patterned metallic screens, ranging from the visible to microwave domains [1–9]. It is well established that enhanced transmission is attributed to the excitation of cavity modes [10, 11] or surface plasmons [12–14]. The concept of extraordinary transmission has further been used in metallic multilayers [15, 16] to develop new optical functionalities, but it remains to be fully investigated for terahertz (THz) and microwave domains [17]. More recently there has been an increased interest in the polarization properties of stacked metamaterials [18–22]. Polarization rotation has been obtained using cascaded metallic hole arrays [23–28], featuring a relatively broad spectral bandwidth with quality factors $Q < 10$. In the same manner, patch-based reflecting arrays were proposed to perform efficient polarization conversion, covering a very broad spectral bandwidth [29–33] with $Q$ close to unity.

In this paper, we propose a stack of periodic metallic polarizers (PMPs) performing polarization-selective rotation of the incident electromagnetic field. Thus, we consider a rotation in such a way that only one component of the transverse electric field is transmitted and rotated by the structure. We demonstrate that stacked PMPs patterned with subwavelength rectangular holes allow for extremely tunable spectral bands. Indeed, we study how such structures are able to achieve either a broadband linear polarization rotation (LPR), with $Q < 10$, and how they are specially adapted to achieve extremely narrowband LPR, with $Q > 10^5$, while ensuring perfect transmission. Specifically, we propose a theoretical study for a number $N \geq 3$ of stacked PMPs to investigate LPR in the THz regime. We show that total LPR is achieved thanks to multiple reflections between the PMPs.

In a previous paper, we theoretically investigated the special case of a two-PMP stack in a polarizer–analyzer configuration [34]. Therein, we demonstrated that the multiple reflections between the two PMPs lead to interesting transmission responses of the structure. Thanks to this phenomenon, we have shown that two stacked PMPs can be used as an ultra-sensitive device for characterizing electro-optical materials in the THz region. It is, however, not adapted for realizing efficient and spectrally tunable LPR. Indeed, two stacked PMPs do not allow for cross-polarization...
rotation and, more generally, perfect transmission cannot be maintained for any polarization rotation angle (see figure 3(a) in [34]).

In section 2, we present a new theoretical model used to describe the LPR effects. Then we give an analytical expression of the transmission to quantify the polarization properties of the structure. In section 3, we design the PMP geometry to selectively achieve optimized broad or narrow spectral bandwidths. We point out that both arbitrary spectral bandwidths and rotation angle values cannot be chosen independently, and we discuss two configurations to overcome this constraint.

2. Description of linear polarization rotation with total transmission

2.1. Theoretical background

We consider a multilayered structure made of identical and parallel PMPs separated by a distance \( h \), as shown in figure 1. Each PMP consists of a periodic array of specific sub-wavelength apertures pierced in a metallic screen, and behaves as a total linear polarizer of the electric field [35]. In this paper, all dielectric and non-metallic regions are filled with air, and metal is assumed to be a perfect electric conductor. Our study involves PMPs patterned with rectangular holes but the results shown in this paper can be readily extended for other particular hole cross-section [35]. In our case, \( a_x \) is the width of the rectangle, \( a_y \) is the length of the rectangle, \( r \) is the period along the \( x \) and \( y \) axes and the thickness of the PMP is denoted by \( t \). All geometrical notations are represented in figure 1 and length units are not mentioned since no dispersion for dielectric materials is taken into account. We investigate stacks of \( N \) PMPs, with \( N \in \mathbb{N}^* \), on which a plane wave falls at normal incidence with an arbitrary electric polarization state. We consider \( N \geq 3 \) in order to obtain polarization-selective rotation phenomena.

For more clarity, let us first describe the special case where we consider a single PMP transmitting along the \( x \)-axis which means that we consider only the first PMP in figure 1. For this PMP we have \( E_T = J^T \vec{E}_{\text{inc}} \) and \( E_R = J^R \vec{E}_{\text{inc}} \) where the transmission and reflection Jones matrices are

\[
J^T = \begin{pmatrix} \alpha & 0 \\ 0 & 1 \end{pmatrix}, \quad J^R = \begin{pmatrix} \beta & 1 \\ 0 & -1 \end{pmatrix}
\]

and \( \alpha \) and \( \beta \) are resonant Airy-like terms in transmission and reflection, respectively [35]. Since we consider stacks of PMPs with identical materials and geometry, the terms \( \alpha \) and \( \beta \) are the same for each PMP and their expressions are given by [35]

\[
\alpha = \frac{4\eta_0 \eta_t}{(C + \eta)^2 - \eta_t^2(C - \eta)^2} |g_0|^2
\]

and

\[
\beta = \frac{2\eta_0[(C + \eta) + \eta_t^2(C - \eta)]}{(C + \eta)^2 - \eta_t^2(C - \eta)^2} |g_0|^2
\]

where \( \eta_0 \) is the relative admittance of the zeroth diffracted order in homogeneous regions and \( \eta \) is the relative admittance of the cavity mode. \( C \) corresponds to the coupling coefficient of diffracted propagative and evanescent waves with the single fundamental mode \( \text{TE}_{01} \) guided inside the apertures, and \( u_t = \exp(ik_0 \rho) \) is the propagation term of the mode inside the apertures. The term \( g_0 \) is the overlap integral between the zeroth order diffracted wave and the \( \text{TE}_{01} \) mode. A more detailed description is given in [35].

Figure 2(a) shows the principle of linear polarization of one PMP where the polarization of electric fields \( E_T \) and \( E_R \) is depicted at resonance. The parameters are \( a_x/r = 0.3 \), \( a_y/r = 0.9 \) and \( t/r = 1 \). Figure 2(b) gives the corresponding
\[ |\alpha|^2 \text{ spectrum (red curve) and } |\beta - 1|^2 \text{ spectrum (green curve), which show two resonances. The peak close to } \lambda/p = 1.76 \text{ is related to the cut-off of the TE}_{01} \text{ mode and the peak close to } \lambda/p = 1.46 \text{ refers to its first Fabry–Perot-like resonance [36].} \]

In this paper, the principle of LPR consists in rotating the incident linear electric field \( \mathbf{E}_{\text{inc}} \) component with respect to the x-axis by an angle \( \theta \) after transmission through the last PMP, as shown in figure 1. Hence, the first PMP is oriented such that its transmitted electric field \( \mathbf{E}_T \) is along the x-axis (term \( \alpha \) of \( J^T \) in equation (1)). In other words, the incident electric field component along the y-axis is not transmitted or rotated but totally reflected by the first PMP and is denoted by \( \mathbf{E}_R \) (term \(-1\) of \( J^R \) in equation (1)). The rotation angle of each PMP axis uniformly changes from 0 to \( \theta \) in the transverse Oxy plane. We introduce \( \varphi \) as the uniform rotation angle between two successive PMPs, so that

\[ (N-1)\varphi = \theta \mod \pi. \]  

We have developed a simple theoretical model which illustrates the physical principle underlying the LPR effect. This present model is a generalized form to an arbitrary number of PMPs \( N \geq 3 \) of the theory previously used for two stacked PMPs in [34]. We analytically deduce the expressions of the transmission and reflection Jones matrices, denoted by \( J^T \) and \( J^R \) respectively, for a stack of \( N \) PMPs:

\[ J^T = \begin{pmatrix} J^T_{x,x} & 0 \\ J^T_{x,y} & 0 \end{pmatrix} = \alpha_N (\cos \varphi)^{N-1} \begin{pmatrix} \cos \theta & 0 \\ \sin \theta & 0 \end{pmatrix}, \] (5)

and

\[ J^R = \begin{pmatrix} J^R_{x,x} & 0 \\ 0 & J^R_{y,y} \end{pmatrix} = \beta_N \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix} - I_d, \] (6)

where \( I_d \) is the identity matrix. The terms \( \alpha_N \) and \( \beta_N \) correspond to the Airy-like spectral resonant coefficients for the whole structure. Their analytical expressions are obtained by using an iterative process that account for PMP stacking. More details can be found in [34, 37]. After tedious calculations, the coefficients \( \alpha_N \) and \( \beta_N \) in equations (5) and (6) are

\[ \alpha_N = \frac{\alpha_{N-1} - \alpha u}{\gamma_N - u^2(1 - \beta)(1 - \beta_{N-1})}, \] (7)

and

\[ \beta_N = \alpha \frac{\alpha_{N-1}}{\beta_{N-1} - 1} u + \beta, \] (8)

with

\[ \gamma_N = 1 - u^2(1 - \beta \beta_{N-1} \sin^2 \varphi) \frac{\cos^2 \varphi - u}{1 - u^2}. \] (9)

where \( u = \exp(ik_0h) \) is the propagation term in homogeneous layers. Equations (7) and (8) are iterative formulæ where the initial terms \( \alpha_1 \) and \( \beta_1 \) correspond to \( \alpha \) and \( \beta \).

We recall that this theory is restricted to the far-field approximation and it implies that \( h \) is large enough to neglect coupling between evanescent waves at the interfaces of two successive PMPs [34, 35]. Thus, the transmission involves only propagating electromagnetic fields which are reduced to the zeroth diffracted propagative order in the spectral range considered. Nonetheless, the evanescent waves in homogeneous regions are taken into account in the transmission and reflection properties of each PMP through the coupling coefficient \( C \) (see equation (6) in [35]). Besides, the wavelength validity domain of the theory is chosen such that only the \( \text{TE}_{01} \) mode exists inside rectangular apertures.

2.2. Total transmission of linear polarization rotation

To study the transmission properties of our structure, we define the transmission \( T \) such that

\[ T = |J^T_{x,x}|^2 + |J^T_{y,y}|^2 = |\alpha_N (\cos \varphi)^{N-1}|^2. \] (10)

It is important to notice that the transmission is an intrinsic property of the structure and does not depend on the incident light polarization. We first investigate the case \( N = 3 \). The
parameters are $a_1/p = 0.3$, $a_2/p = 0.9$, $t/p = 1$ and $\varphi = 45^\circ$ ($\theta = 90^\circ$). Figure 3 shows the transmission versus $\lambda/p$ and versus the distance between polarizers $h/p$ in linear and logarithmic scales, respectively. The quantity $h/p$ is therefore chosen as equal to 1, i.e., such that at least two distinct resonant transmission peaks occur in $\lambda/p \in [1.2, 2.0]$ (see green dotted line in figure 3). The LPR with such parameter values is labeled $A$ in figure 3.

It may be surprising to get total transmission at resonances by simply interposing one linear polarizer at 45° between two crossed ones. According to equation (5), this means that $T = |c_3|^2 [\cos (\pi/4)]^4 = 1$ at resonances. We expect that this total transmission is due to multiple reflections between PMPs [34]. For cascaded dichroic polarizers, where the multiple reflections vanish, $T = |(\cos \varphi)^{N-1}|^2$ which is equivalent to equation (10) with $|\alpha_\Omega| = 1 \forall \lambda/p$. In this case, and for $N = 3$, the transmission reaches only 25% for dichroic polarizers instead of 100% at resonance of the PMP, as shown in figure 3. This agrees perfectly with the classical Malus law and demonstrates that the multiple reflections between PMPs are responsible for the observed total transmission at resonance.

We may also expect that peak positions are largely dependent on the thickness $h$ of the homogeneous layer because of these multiple reflections. However, the transmission spectra for different values of $h/p$ shown in figure 3 exhibit peaks with positions that roughly coincide with those of a single PMP ($\lambda/p \approx 1.4$ and 1.68) except when the Fabry–Perot resonances of the cavity formed by two consecutive PMPs intersect the PMP’s own resonances, which are independent of $h$ (see oblique blue dotted line in figure 3). We believe that such a total transmission is a complex phenomenon outside of the scope of this paper. Nevertheless, a more detailed analysis can be found in [34].

### 3. Spectrally tunable linear polarization rotation

In this section, we show that the arrangement of the structure, as well as the hole geometry, play a crucial role in controlling the quality factor of the LPR. However, the polarization direction of the rotated output field, given by $\theta$, and the quality factor, which can be influenced by $\varphi$, cannot be arbitrarily and simultaneously fixed. Hence, we first focus on the angle $\varphi$ with no consideration for $\theta$.

From now on we restrict our study to the peak close to $\lambda/p = 1.68$, which is related to the cut-off of the TE$_{01}$ guided mode inside the rectangular holes. However, the cut-off wavelength of the TE$_{01}$ mode is equal to $2a_2$. This implies that the same value of $a_2$ must be kept in order to avoid important peak shifts. Section 3.1 considers the design of broadband LPR (BPR), which corresponds to a low quality factor ($Q < 10^5$). Then, we discuss the limitations of BPR. Conversely, in section 3.2 we design a narrowband LPR (NPR) which corresponds to ultra-high quality factors ($Q > 10^5$).

#### 3.1. Broadband linear polarization rotation

First, $a_1/p$ must be chosen to be as large as possible to obtain BPR. Nevertheless, the value of $a_1/p$ must be chosen such that the cut-off frequency of the second mode TE$_{01}$ remains smaller than the first Rayleigh–Wood frequency. In our case, the maximum value of $a_1/p$ is 0.5. Results shown in figure 4(a) confirm that the width of transmission peaks increases when $a_1/p$ grows. Precisely, figure 4(b) shows the quality factor $Q = \lambda_0/\Delta \lambda$ computed for the peak close to $\lambda/p = 1.68$, for which $\lambda_0$ is the normalized central values of peaks and $\Delta \lambda$ corresponds to the full width at half maximum. It particularly shows that $Q$ decreases when the width of the rectangle, $a_1/p$, increases. Thereafter, we fix $a_1/p = 0.5$ for BPR. The BPR with such parameter values is labeled $B_0$ in figure 4(b) with $Q = 18.4$.

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**Figure 3.** Transmission spectra for different values of $h/p$ for $N = 3$. Other parameters are $a_1/p = 0.3$, $a_2/p = 0.9$, $t/p = 1$ and $\theta = 90^\circ$ ($\varphi = 45^\circ$).
Figure 4. (a) Transmission spectra for different values of $a_x/p$ for $N = 3$. (b) Quality factor $(Q)$ and spectral position $(\lambda_0/p)$ of the peak close to $\lambda/p = 1.68$. Other parameters are $a_x/p = 0.9$, $t/p = h/p = 1$ and $\theta = 90^\circ$ ($\varphi = 45^\circ$).

Figure 5. (a) Variations of quality factor of the peak close to $\lambda/p = 1.68$ with respect to $\varphi$ and for different values of $N$. Variations of the peak positions are shown in the inset. Other parameters are $a_x/p = 0.5$, $a_y/p = 0.9$ and $t/p = h/p = 1$. (b) Transmission spectra for different values of $t/p$ for $N = 3$. The transmission spectra for $t/p = 1$, $t/p = 1.1$ and $t/p = 2$ are shown in the inset. Other parameters are $a_x/p = 0.5$, $a_y/p = 0.9$, $h/p = 1$ and $\varphi = 0.5^\circ$.

Figure 5(a) shows the variation of $Q$ with respect to $\varphi$ and for different values of $N$. As expected, the quality factor decreases when $\varphi$ decreases. Similarly to photonic crystal band gap broadening, quality factors tend to one limit for a fixed value of $\varphi$ when the number $N$ of cascaded PMPs increases. We also remark that a BPR with $N = 3$ has an identical performance at $\varphi = 0.5^\circ$ to a BPR with $N = 15$. The BPR with $N = 3$ and $\varphi = 0.5^\circ$ is labeled as $C_B$ in figure 5(a), for which $Q = 7.9$. The inset graph in figure 5(a) reveals that the peak position remains almost constant near $\lambda_0 \approx 1.65$.

Another idea for broadening the bandwidth is to merge the peaks by shifting the peak centered to $\lambda/p \approx 1.4$ to the one centered to $\lambda/p \approx 1.68$. The peak close to $\lambda/p = 1.4$ is related to a Fabry–Perot-like resonance of the TE$_{01}$ cavity mode and its resonance wavelength changes with the metal thickness $t$. The position of the peak near $\lambda/p = 1.68$, related
to the cut-off of the TE$_{01}$ cavity mode, is not affected by $t/p$ values because it only depends on $a_s$. Figure 5(b) depicts transmission spectra for different values of $t/p$. As expected, we see that the two peaks merge but the bandwidth of each peak narrows when $t/p$ increases. The spectra shown in the inset of figure 5(b) computed for a BPR with $t/p = 2$, and labeled as $D_B$, reveals a relatively low quality factor, $Q = 3.29$. As we can observe in the inset spectra of figure 5(b), it is possible to modulate the spectral bandwidth, or in other words the quality factor $Q$, at a $-3$ dB threshold while the bandwidth at $-6$ dB is barely affected by the variation of $t$. Those results show that it is possible to lower the quality factor by increasing the width of the rectangle, by reducing the angle $\varphi$ and by carefully choosing the layer’s thickness $t$. At the same time, they demonstrate that $Q$ converges to a limit value. These multilayered devices present transmission properties close to the cascaded nanobar structure studied in [26]. It features a similar broadband range with a very efficient LPR obtained by twisting.

As mentioned above, the relation between $\varphi$ and $\theta$ given by equation (4) does not allow us to choose an accurate quality factor $Q$ and an arbitrary angle $\theta$ simultaneously. This issue is especially crucial for the achievement of a low $Q$ and tunable LPR. For example, in the case of cross-polarization rotation where $\theta = 90^\circ$ and with $N = 3$, the angle $\varphi$ is necessarily equal to $45^\circ$ (see section 2.4). Such a value of $\varphi$ is not optimized to obtain a low-$Q$ cross-polarization rotation. In this case, the corresponding quality factor is $Q = 11.3$ for $\lambda_0 \approx 1.68$. Thus, we discuss two options to overcome this limitation.

The first option simply consists in increasing $N$ in order to reduce $\varphi$ and therefore lower the quality factor. Figure 6(a) shows the transmission spectra for different values of $N$ for $\theta = 90^\circ$. As expected from section 3.1, we observe a broadening of the transmission spectra when $N$ increase. However, figures 5(a) and 6(a) show that such a broadening is limited and converges to a finite spectral bandwidth (convergence of $Q$ when $\varphi \rightarrow 0^\circ$). Consequently, a reasonable number of polarizers should be chosen to achieve a good trade-off between a large bandwidth and a realistic device.

Figure 6. (a) Transmission spectra for different values of $N$ for $\theta = 90^\circ$ with $a_s/p = 0.5$, $a_s/p = 0.9$, $t/p = h/p = 1$. (b) Transmission spectra as a function of $\chi_2$, the angle between the second and the third (last) PMP, with $\chi_1 + \chi_2 = \theta$ and $\theta = 90^\circ$.

The second option is to consider a non-uniform angle $\chi$ between each plate for a stack of $N$ polarizers such that $\sum_{i=1}^{N-1} \chi_i = \theta$ with $i \in \{1, 2, \ldots, N - 1\}$. Precisely, we study the simple case of $N = 3$ with $\chi_1 + \chi_2 = 90^\circ$; figure 6(b) shows the transmission spectra as a function of $\chi_2$. It is important to note that the transmission spectrum is optimized when $\chi_1 = \chi_2 = 45^\circ$ featuring a perfect transmission with the lowest $Q$. Thus, breaking the intermediate rotation angle $\varphi$ into different values $\chi_i$ is not efficient for achieving total and low-$Q$ LPR. Nevertheless, figure 6(b) also shows that the structure exhibits an angular tolerance within which its performances are barely affected.

3.2. Narrowband linear polarization rotation

Contrary to BPR, $a_s/p$ must be chosen to be as small as possible in order to obtain NPR. Hence, the value of $a_s/p$ is fixed to 0.1 which corresponds to the polarization rotation labeled $B_N$ in figure 4(b). For this value of $a_s/p$ and for $N = 3$, the peak close to $\lambda/p = 1.77$ shown in figure 4(a) splits into two peaks. The quality factor plotted in figure 4(b), equal to 29.7 at $B_N$, is computed for the global peak. We assume that this effect is due to resonance degeneracy. The whole structure may be seen as a stack of five cascaded and coupled resonators. Indeed, for $N = 3$, there are three PMP resonators coupled to two multiple-reflection resonances located in the two homogeneous regions. This complex behavior deserves a thorough analysis in a future work. The narrow peaks are indicated by dark arrows in figure 7(a). Precisely, we see in the graph on the left of figure 7(a) that the narrowest peak is becoming increasingly thinner when $\varphi$ tends to $90^\circ$ while the other ones disappear. In general, $N - 1$ peaks exist for $\varphi$ getting closer to $90^\circ$, one of which presents a relatively broad spectral bandwidth with $T < 1$, while the $N - 2$ other ones are very narrow peaks with $T = 1$ at resonances. In order to distinguish the peaks more easily, the peaks are also shown in the lower inset spectra in figure 7(a) for $\varphi = 30^\circ$. It is interesting to note that, for fixed values of $N$, all narrow peaks seem to converge to a unique value of $\lambda/p$ when $\varphi$ increases. Thereafter, we study in particular the nearest peak to $\lambda/p = 1.68$. 
We are now interested in the variation of the quality factor of the chosen transmission peak when $\varphi$ tends to 90°. The results are depicted in figure 7(b) and reveal that the quality factor drastically diverges when $\varphi$ tends to 90° and for different values of $N$. As an example, the NPR with $\varphi = 89^\circ$ and $N = 3$ is labeled as $C_N$. For this case, $Q$ reaches $1.3 \times 10^5$, and the transmission spectra are plotted in the inset graph on the right of figure 7(b). In the inset graph on the left, we remark that peak positions converge to a unique value of $\lambda/p$ when $\varphi$ increases, confirming the observation made in figure 7(a). This interesting result could be used for the design of high-quality filters for the THz spectral band. Nevertheless, in view of the experimental demonstration, the robustness of the structure with respect to the fabrication imperfections should be discussed. However, the latter greatly depend on the manufacturing process, which is not yet established. A parametric study involving pure numerical methods, such as the finite difference time domain [38].

4. Conclusion

We have theoretically investigated a total LPR with an extremely tunable spectral bandwidth. More specifically, the polarizing devices consisted of stacks of PMPs separated by dielectric layers. The numerical results are supported by a new and efficient model from which the Jones matrices of such stacked structures are analytically expressed. The optimized LPR is achieved by regularly rotating successive PMPs to mimic a chiral structure. Furthermore, we have underlined the influence of the width of the rectangular holes and, more importantly, the angle $\varphi$ to selectively achieve a broadband or narrowband LPR. Precisely, we have shown that a low quality factor ($Q < 10$) and a high quality factor ($Q > 10^5$) can be obtained. Such flexible metadevices could be applied for the design of broadband linear cross-polarization rotators or high-$Q$ filters, which represent important cornerstones in optical communications.

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