Localized shape resonance on silver film perforated by H-shaped and more complex shaped hole arrays

Fang-Tzu Chuang, National Taiwan University
Localized shape resonance on silver film perforated by H-shaped and more complex shaped hole arrays

Hao-Fu Huang, Yu-Wei Jiang, Hung-Hsin Chen, Yi-Ting Wu, Yi-Tzung Chang, Fang-Tzu Chuang, and Si-Chen Lee*

Department of Electrical Engineering, Graduate Institute of Electronics Engineering, National Taiwan University, Taipei 106, Taiwan
*selee@cc.ee.ntu.edu.tw

Abstract: The experimental results of light transmission through periodic array of H-shaped hole and more complicated hole which is a combination of multiple U shape are demonstrated. The observations indicate that the localized shape resonance in the longest resonant length of unfolded U-shaped part of the hole always appears. However, localized modes resonant in smaller U-shaped length don't always appear. Localized mode with non-U-shaped resonant path cannot be seen in our sample. In addition, localized mode with different order and resonant path can be excited by different polarized light.

OCIS codes: (240.6680) Surface plasmons; (230.7370) Waveguides; (260.5740) Resonance; (050.1940) Diffraction; (260.3090) Infrared, far.

References and links


1. Introduction

Extraordinary optical transmission (EOT) through a metal film perforated by periodic hole arrays was discovered by Ebbesen [1,2], which was attributed to the excitation of surface plasmon polariton (SPP) at the metal-dielectric interface. The theoretical behavior of EOT was discussed by Genet and Liu [3,4]. However, from the broad aspects of the enhanced
transmission, the EOT can be attributed to not only the SPP but also the localized shape resonance (LSR). Klein proved that the shape resonance originated from the contribution of single hole by arranging the rectangular holes randomly [5]. Different from circular hole, as the resonance close to cutoff frequency, individual rectangular hole can exhibit enhanced strong transmission, and the peak transmittance can be tuned by the aspect ratio of the rectangle [6]. The transmission through C-shaped and H-shaped hole arrays were studied [7–9]. It is revealed that transmission peak shift to a shorter wavelength when the arm width of H-shaped hole is increased. Lee’s research [8] revealed that the resonant wavelength of localized mode is related to the unfolded C-shaped hole length [8]. And the transmission behavior through H-shaped under different incident polarized light was also investigated [9]. However, the transmission characteristics through H-shaped hole and more complex shaped hole, including localized shape resonance effect have not been studied comprehensively. It is interesting to investigate the resonant behaviors of localized mode for H-shaped hole and more complex shaped hole. Also, it is rare to study the polarized light interaction with LSR modes having different resonant wavelength.

In this paper, metal films perforated by H-shaped and more complex shaped hole whose shape is the combination of multiple U and H shape are prepared to study the effect on the transmission spectra and the dispersion relation of LSR.

2. Experiment

Figure 1(a) and 1(b) display the top and side views of the metal hole array arranged in square lattice, respectively. Also shown are the definition of the geometrical parameters of metal hole array. The 75 nm thick silver film was deposited on the periodic photoresist island arrays and lifted off to form the perforated hole array on top of a doubly-polished silicon wafer. The period (Λ) of hole array and the hole width (w) are fixed at 14μm and 1μm, respectively. The total sample size is 0.6 × 0.6 cm². A Bruker IFS 66 v/s Fourier-Transform Infrared (FTIR) spectrometer is adopted to measure the transmission spectra. The dispersion relation along x direction was measured by rotating sample around y axis 1° per step from 0° to 50°.

![Fig. 1. Definition of the parameters of H-shaped hole arrays in a square lattice, (a) top view and (b) side view.](image)

3. Transmission results and discussions

Figure 2(a) shows the top view and structure parameter of samples 1(U shape) to 3(H shape). Figure 2(b) displays the zero-order transmission spectra at normal incidence of these three samples. The transmission spectra changes obviously when the hole shape change from U to H shape. In order to investigate the transmission spectra in more detail, the transmission dispersion relation were measured.
Fig. 2. (a) Top view and structure parameter of samples 1 to 3. (b) Zero-order transmission spectra at normal incidence of samples 1, 2, 3. The vertical red dash line represents the theoretical position of degenerated (1, 0) Ag/Si mode.

Figure 3(a)–3(c) show the measured transmission dispersion and their mode analysis curves for samples 1 to 3, respectively. Rectangular hole exhibit strong shape resonance which would happen when the resonant wavelength is close to cut-off wavelength of the rectangular waveguide. The horizontal bright line or horizontal bright area in Fig. 3 are the localized shape resonance (LSR). The flatness of the dispersion relation is the strong evidence for highly localized feature of the resonant modes that mediate the transmission. The transmission spectra position of LSR can be calculated by the equation [6]

$$\lambda_{res} = \lambda_{cut-off} = \frac{2n_{eff} L_{res}}{m}, \quad n_{eff} = \sqrt{\frac{n_{si}^2 + n_{air}^2}{2}}, \quad m = 1, 2, 3, \ldots$$

(1)

Where $L_{res}$ is the resonant length and $n_{eff}$ is the effective refractive index inside the metal holes. The sample structure in this study is a sandwich structure. The periodic metal structure is sandwiched between the Si substrate ($n_{Si} \approx 3.45$) and air ($n_{air} = 1$). A transmission-line model that describes the effective index variation with different substrate was supplied [10,11]. The value of $n_{eff}$ was determined by Eq. (1) which is about 2.4 to 2.5 in this study [12]. The LSR mode at 0.0124eV of sample 1 with U-shaped hole in Fig. 3(a) is recognized as 1st LSR where the $L_{res}$ is the unfolded length of U-shaped hole. Similarly, the horizontal line at 0.0136eV in Fig. 3(b) and 0.0155eV in Fig. 3(c) are the 1st LSR of samples 2 and 3, respectively. According to Eq. (1), the resonant length $L_{res}$ of LSR can be obtained and summarized in Table 1. The resonant length of LSR is close to the value ($L_{U}$) of green path in Fig. 2(a). It reveals that the light would be guided along green path. In others words, for sample with H-shaped hole, light travel along U-shaped part of the hole. Moreover, for sample 2 with asymmetric H shape hole, the resonant length of LSR is close to the length of unfolded larger U shape. That means light would travel along longer U shape path(green dash line path) rather than the shorter one(blue dash line path).

Fig. 3. The dispersion relation of transmission spectra and their modes analysis for samples (a)1, (b)2, (c)3. The green and red dash lines are theoretically calculated curves of LSR and Ag/Si SP modes, respectively.
Table 1. Measured and theoretical LSR position of sample 1 to 6

<table>
<thead>
<tr>
<th>Sample</th>
<th>( L_x (\mu m) )</th>
<th>( L_U (\mu m) )</th>
<th>Measured resonant length ( L_{res} (\mu m) )</th>
<th>Measured 1st LSR(( \mu m ))</th>
<th>Theoretical 1st LSR(( \mu m ))</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>8</td>
<td>22</td>
<td>20</td>
<td>100</td>
<td>110</td>
</tr>
<tr>
<td>2</td>
<td>8</td>
<td>19</td>
<td>18.2</td>
<td>91</td>
<td>95</td>
</tr>
<tr>
<td>3</td>
<td>8</td>
<td>15</td>
<td>16</td>
<td>79.8</td>
<td>75</td>
</tr>
<tr>
<td>4</td>
<td>5.64</td>
<td>12.64</td>
<td>14.6</td>
<td>73</td>
<td>63.2</td>
</tr>
<tr>
<td>5</td>
<td>9.55</td>
<td>16.55</td>
<td>18.2</td>
<td>91</td>
<td>82.8</td>
</tr>
<tr>
<td>6</td>
<td>11.6</td>
<td>18.6</td>
<td>19.6</td>
<td>97.8</td>
<td>93</td>
</tr>
</tbody>
</table>

Resonant length \( L_{res} \) are calculated using Eq. (1). The \( L_U \) represents the unfolded \( U \)-shaped part length of each hole as the green dash line path shown in Fig. 2(a) and 4(a). The theoretical LSR are calculated by Eq. (1) using the value \( L_U \).

In order to verify the resonance length of LSR for sample with H-shaped hole, we change the value \( L_x \) of H shape hole. The structure parameter and top view of samples 4 to 6 are displayed in Fig. 4(a). The value \( L_x \) of samples 4, 5, 6 are 5.64\( \mu m \), 9.55\( \mu m \) and 11.6\( \mu m \), respectively. Figure 4(b) shows the transmission spectra at normal incidence of samples 3 to 6. Comparing Fig. 4(b) and their dispersion relation (not shown), it is realized that peaks at 73\( \mu m \), 91\( \mu m \) and 97.8\( \mu m \) shown in Fig. 4(b) are 1st LSR. And the resonant length of LSR are calculated and summarized in Table 1. The measured \( L_{res} \) are also close to the length \( L_U \) of green path in Fig. 4(a). Although the length of \( L_x \) changes, the resonant length of LSR are the \( U \)-shaped part of the H shape hole. It seems that there is no other resonant path of LSR in H shape hole.

![Fig. 4. (a) Top view and structure parameter of samples 4 to 6. (b) Zero-order transmission spectra at normal incidence of samples 3 to 6. The vertical red dash line represents the calculated position of degenerated (1, 0) Ag/Si mode.](image)

Now the hole shape is designed to be more complex. Figure 5(a) and 5(b) show the top view and geometric parameters of sample 7 to 9 and 10 to 12, respectively. The period of hole array are both 14\( \mu m \) in x and y direction. The hole shape of these samples are the combination of multiple \( U \) shape (or \( H \) shape). For example, for sample 7, two \( U \) shape holes are put together so the hole looks like “E” shape. It is expected that the structure with complicated shape would lead to more complex shape resonance characteristics. From the discussion of LSR on H-shaped hole mentioned above, it is reasonable to infer that the resonant length of LSR might be the \( U \)-shaped part of these complicated shape holes as well. For sample 7, 8, and 9, there are two types of \( U \)-shaped resonance length which are green and blue path as labeled in Fig. 5(a). Figure 6(a) to 6(c) display the measured dispersion relation and their mode analyses of samples 7 to 9. The red dashed line indicates the SP modes. The green and
blue dashed lines are the theoretical dispersion curves of LSR modes whose $L_{\text{res}}$ are the green and blue path as labeled in Fig. 5, respectively. It is found that the LSR modes whose $L_{\text{res}}$ is the green path would appear for these samples. However, the LSR modes whose $L_{\text{res}}$ is the blue path appears only in sample 9. For these samples, the $L_{\text{res}}$ of LSR mode represent the light would be guided in larger U-shaped part of hole. For comparison, the samples 10 to 12 with more complicated hole shape are investigated. In these samples, there are three kind of U-shaped path which are shown in Fig. 5. The green, blue, pink paths represent largest, medium, smallest U-shaped part of the hole, respectively. Figure 6(d) to 6(f) display the measured dispersion relation diagrams of samples 10 to 12, respectively.

Fig. 5. Top view and structure parameters of samples (a) 7 to 9 and (b) 10 to 12.

In Fig. 6, it can be seen that the green LSR mode with largest U-shaped $L_{\text{res}}$ appear for all samples. The pink LSR mode with smallest U-shaped $L_{\text{res}}$ appear in samples 10 and 12. The blue LSR mode with middle U-shaped $L_{\text{res}}$ seems not appear for all samples. The pink and blue LSR mode can’t always be observed for samples 10 to 12. For the experimental data of samples 7 to 12, it can be observed that the LSR mode with largest U-shaped resonant length would dominate. The LSR mode with smaller U-shaped $L_{\text{res}}$ cannot always be seen. The reason for LSR modes with smaller U-shaped $L_{\text{res}}$ don’t always appear might due to the coupling effect with SP. For example, in Fig. 6(e), the theoretical 2nd LSR with blue resonant path located at 0.023eV and 2nd LSR with pink resonant path is at 0.027eV. However, the spectra position of these modes is close to the $(-1, 0), (1, 0)$ and $(0, \pm 1) \text{Ag/Si SP}$. These LSR modes may couple to SP so no horizontal LSR mode appears in dispersion relation.
For rectangular hole, the light polarization direction also plays an important role. It is interesting to investigate the transmission spectra of complex shaped hole with incident light under different polarization because the electric field must affect the shape resonance. Figure 7(a) to 7(d) display the transmission spectra with x- and y-polarized light at normal incidence for samples 3, 4, 7, 9, respectively. From Fig. 7(a) and 7(b), the sample with H-shaped hole, it is found that the different peaks appear at different polarization. It seems that 1st LSR appear with x-polarized light. However, the 2nd LSR is excited by y-polarized light. There are similar phenomenon for sample with complex shaped hole. In Fig. 7(c), sample 7, the broad band peak at about 140μm is 1st LSR which is excited by x-polarized light. The resonant path is the green dash line path (largest U-shaped path) as labeled in Fig. 5. And the 2nd LSR (with largest U-shaped resonant path) peak at about 69μm is excited by y-polarized light. However, different phenomenon are observed for LSR with smaller U-shaped resonant path. For sample 9, in Fig. 7(d), 1st LSR with blue resonant path (smaller U-shaped path) at 72μm is excited by y-polarized light. It seems that LSRs with different order and resonant path are excited by different polarized light. For LSR with largest U-shaped resonant path, 1st LSR is excited by x-polarized light but 2nd LSR is excited by y-polarized light. For smaller U-shaped resonant path, the 1st LSR may excited by y-polarized light. We can design H or U shape hole with different parameters and use polarized light to filter various peaks out.

Fig. 6. The dispersion relation of transmission spectra for samples (a) 7, (b) 8, (c) 9, (d) 10, (e) 11, (f) 12 with their mode analyses. The red dash lines are Ag/Si SP modes. The green and blue dash lines represent calculated LSR modes with different $L_{\text{res}}$. 

Received 4 Jan 2011; accepted 11 Jan 2011; published 4 Mar 2011

(C) 2011 OSA

14 March 2011 / Vol. 19, No. 6 / OPTICS EXPRESS  5230
Fig. 7. Zero-order transmission spectra at normal incidence with x- and y-polarized light for samples (a)3, (b)4, (c)7, (d)9, respectively. The vertical red dash line represents the theoretical position of degenerated Ag/Si mode.

4. Conclusions

In conclusion, the transmission spectra through samples with periodic H-shaped hole and more complicated hole are investigated. The observations indicate that the resonant length of localized shape resonance is the length of unfolded U-shaped part of the hole. The LSR modes with smaller resonant U-shaped length don’t always appear. However, The transmission spectra reveal that the LSR mode with largest resonant U-shaped part of the hole could always appear. LSR mode with non-U-shaped resonant path cannot be seen in our sample. In addition, LSR with different order and resonant path can be excited by different polarized light.

Acknowledgement

This research was carried out with the financial support of the National Science Council of the Republic of China under the Contact No. NSC 99-2120-M-002-002.