Optical transmission through MDM plasmonic tri-layer consisting of T and L shape periodic structures

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ABSTRACT
Optical transmission properties of plasmonic MDM (metal–dielectric–metal) tri-layer consisting of T and L shape periodic slits are investigated by finite difference time domain method. The spectral transmission in the range of visible to NIR (near-infrared) frequencies greatly depends on the slit structure. For T shape structure, single resonant transmission peak is observed, while L shape structure shows double resonance behaviour. The present study shows how structural shapes and polarizations of incident light determine the resonant condition. Based on the observed transmission spectra, an LC circuit model is presented. The low-frequency resonant peak is observed to be sensitive to the structural shape. The presence of side channel oriented parallel to the polarization direction of the input beam is responsible for the origin of high-frequency band (visible-end) in “L” shape structure. The present plasmonic structure is useful in optical transmissive devices.

1. Introduction
Plasmon-induced transparency (PIT) in subwavelength asymmetric metamaterials structures recently creates huge interest due to novel transmission properties and accessibility to the induced frequency band [1–4]. Metal–dielectric–metal (MDM) and metal–semiconductor–metal structures have wide applications in designing optical and optoelectronic devices [5–13]. Surface plasmon resonance plays a vital role in enhancing optical properties and device performances [14–16]. Shape and size, separation (gap) between plasmonic elements, and periods significantly modify the resonance conditions [17,18,19–21], which may lead to controllable optical transmission at optical to IR spectral range [22–32]. New transmission band or splitting of the band can occur due to strong electromagnetic near-field interactions caused by localized and propagating surface plasmons [19,27,33–38]. MDM plasmonic tri-layer consisting of an array of asymmetric shape slits is an interesting optical system that exhibits complex transmission properties. Plasmonic interactions and waveguiding properties are often considered to analyse this complex transmission [27,33,39]. MDM tri-layer system can offer controllable transmission depending upon the presence of dielectric materials between two metal layers. The dielectric spacer layer can be sensitive to thermal energy (such as vanadium oxide: VO\textsubscript{2}) or electrical bias, such that the dielectric value can be tuned by the means of external source parameters. Recently, we have demonstrated “H” shape plasmonic metasurface that has novel transmission and switching properties [40]. In the present study, resonant optical transmissions through “T” and “L” shaped plasmonic slit structures (Figure 1) are investigated in the spectral range of visible to NIR (near-infrared) frequencies. The influence of structural asymmetry and incident beam polarization is also studied to know the transmission characteristics. The results are compared with that obtained from the single-layer structure made of a metal only layer of identical structural configuration to identify the influence of dielectric spacer layer on the optical transmission.

2. Design parameters and numerical simulation
Optical transmission (ratio of the transmitted power to the incident power) through plasmonic MDM tri-layer is investigated using finite difference time domain (FDTD) calculation (OPTIWAVE: 32 bit). “T” and “L” shape subwavelength structures have the following design parameters: air slits of length ($l$), width ($w$) and MDM layer thickness ($h$) are 200, 50 and 100 nm (40 + 20 + 40 nm), respectively (for single-layer system, the gold layer thickness is 100 nm). Silica (SiO\textsubscript{2}) layer of thickness...
Figure 1. Schematic representation of plasmonic MDM tri-layer unit cell having “T” shape (left) or “L” shape slit structure (right). The design parameters are noted as $l = 200$ nm, $w = 50$ nm, $h = 100$ nm (metal: 40 nm + dielectric: 20 nm + metal: 40 nm). Each unit cell has a dimension of 300 nm ($p_x \times p_y$) and contains one “L” or “T” air-slit at the centre as in the figure. The excitation beam is launched as shown in the figure with electric field vector ($E$) pointing along the $X$-direction (unless otherwise stated).

200 nm having a constant refractive index ($n$) of 1.5 is considered as the supportive layer. The dielectric layer sandwiched between two metal layers has a typical thickness of 20 nm and is made of SiO$_2$ (constant refractive index of 1.5). It is noteworthy that the “T” and “L” shaped structured metasurface can be fabricated using sophisticated nanofabrication tools such as electron beam lithography and focused ion beam technique. The periodicity of the unit cell is considered as 300 nm (square type) along the $x$ and $y$ directions. Periodic boundary condition (PBC) along the $x$ and $y$ directions, and anisotropic perfectly matched layers (APML) in the $z$-direction is applied. Au layer is considered to have the Lorentz–Drude dispersive behaviour [41]. A Gaussian-modulated continuous light wave is launched normally whose polarization is set as mentioned in the respective section. The central wavelength of the incident light pulse is set to 0.75 µm. The half-width and time offset are set to $1 \times 10^{-15}$ and $4 \times 10^{-15}$ s, respectively. The input beam polarization is set as mentioned in the respective sections. For accuracy and convergence, a minimum of 10 cells per wavelength with the meshing of $\leq \lambda/10n$ are used.

3. Simulation and discussion

Visible to near-infrared (Vis-NIR) optical transmission spectra (400–1500 nm) for $x$-polarized incident beam (electric field ($E$) along the $x$-direction) are shown in Figure 2. The spectra for MDM tri-layer and single metal layer are shown in Figure 2(a,b), respectively. In both the cases (tri-layer and single layer), the shape of the subwavelength slit structure is slowly changed from “T” to “L”, and at each step of shape modification, the corresponding spectrum was obtained as shown in the figure. For the tri-layer system, the transmittance spectrum for T-shaped structure shows a single resonant transmission band at $\sim 1050$ nm, which corresponds to the channel waveguide mode. The broad peak has a full width at half maximum (FWHM) of $\sim 275$ nm. When the shape changes to “L” shape, the resonant transmission peak red-shifts to $\sim 1175$ nm (with FWHM of $\sim 325$ nm). An additional peak appears at the lower wavelength centred at $\sim 750$ nm. The gradual change in shape (T to L) results in the spectral change, showing gradual red-shifts in high wavelength peak and blue-shifts in low wavelength peak. Similar observations are made for a single-layer system [28,41]. The T-shaped structure shows single resonant transmission at $\sim 975$ nm with the FWHM of $\sim 225$ nm. When the structure changes from T shape to L shape, the resonant peak is observed at $\sim 1125$ nm with FWHM $\sim 325$ nm. It is noted here that in the case of the tri-layer system, the FWHM is broad and the high wavelength peak is more asymmetric. The observed resonant frequency can be calculated by considering the resonant LC circuit model. For simplicity, we have considered single-layer system for the calculation (Figure 3). Further, capacitance and inductance of the periodic T- or L-shaped structures are calculated based on the unit cell geometry. The formula for the inductance ($L$) is taken from the references [42,43], and as written in Equation (1) ($L$ in microhenry). Here, $l$ is the length of the inductor, $a$ the width and $b$ breadth (in this case, $b = h$).
The capacitance of the air-slit can be calculated as, $C = \varepsilon_0 A/d$. We can write the effective impedance of the T and L array structures as in Equation (2), where, for L shape, the $L_2$ in Equation (2) will be replaced by $(L_{2a} + L_{2b})/2$. Using the above formulas, the resonant frequencies (low frequency) can be calculated for T and L shape structures as in Equation (3). The calculated low-frequency resonant transmission peak (according to Equation (3)) is found to be $\sim 485$ nm and $\sim 570$ nm for T- and L-shaped structures, respectively. These calculated values are approximately two times less than the computed values. This is due to the retardation effect of metallic structure at optical frequencies [40]. Further, it is noteworthy that the observed red-shift in the low-frequency resonant peak arises due to the increase in the effective inductance of the system when the structure changes from T shape to L shape.

$$L = 0.2l \left[ \ln \left( \frac{2l}{a+b} \right) + 0.5 \right]$$
$$\frac{1}{Z_{T,L}} = \frac{2}{j\omega L_0} + \frac{1}{2j\omega C_1} + \frac{1}{2j\omega L_2 + \frac{1}{j\omega C_2}}$$
$$\omega_{T,L,\text{low}} = \sqrt{\frac{1}{2L_2C_2}}$$

Polarization-dependant optical transmission spectra for single and tri-layer systems containing L-shaped structures are studied and the spectra are shown in Figure 4. The “L” shape structure is considered as it is more asymmetric in nature. The orientation of the polarization direction is as indicated in the inset of Figure 4. When the input beam is linearly x-polarized, the transmission spectra for both the systems show two resonant transmission peaks. The resonant peak positions (775 and 1200 nm) for the tri-layer system are slightly different compared to that (725 and 1100 nm) for the single-layer system. When the input polarization orientation is changed from linear $x$-pol to 45°-pol, a significant change in the spectra is observed for both the cases (single-layer and tri-layer systems). Only low-frequency (high wavelength) resonant transmission band is observed at this polarized light excitation. At this polarized light excitation, the spectral peak positions for single-layer system as well as tri-layer system are slightly at different spectral positions. Further, due to the symmetry of “L” shape structure with respect to polarization (45°-pol) only high wavelength channel waveguide mode is observed.

The origin of low-frequency resonant transmission band for “L” shape structure is now investigated for the single-layer and tri-layer systems. For asymmetric “L” structure, side channel plays a crucial role. Here, the x-length (parallel to the direction of $x$-pol) is reduced step by step and at each step optical transmission spectra is monitored. The x-length-dependent optical transmission spectra are shown in Figure 5. In the case of the tri-layer system, the reduction in the x-length results in a blue-shift of low-frequency eigen mode (dark-green, red and black coloured curves). The high-frequency band also blue-shifts but gradually becomes less prominent. Finally, when x-length becomes zero, i.e. when “L” becomes simply a single slit oriented along the direction perpendicular to the direction of $x$-pol, only a single resonant transmission band at $\sim 875$ nm is observed. A small hump at $\sim 1100$ nm is also noted in this case. For the single-layer system, a similar shift in the resonant transmission band (transmission peak at $\sim 1050$ to $\sim 850$ nm) is observed. It is noted that no hump $\sim 1100$ nm is seen in this case. Thus, hump at $\sim 1100$ nm in the tri-layer system is attributed to the plasmonic interaction between the symmetric interfaces on either side of the SiO2 dielectric layer. Plasmonic interaction noticeably broadens FWHM of the low-frequency band in the tri-layer system, and is clearly seen in the spectra.
It is observed that the x-length ($L_x$) dependent shift of low-frequency band is not monotonic. A plot of the low-frequency peak position versus $L_x$ is presented in Figure 6, indicating the perturbation by the presence of side channel. An empirical second-order polynomial fit shows a saturation trend due to the optimum interaction of side channel and is discussed further in the next section.

The waveguide mode which depends on the slit length and shape remains unchanged, although the overall resonant transmission is affected by the presence of plasmonic interaction. This is supported by the analysis of electric field distributions across the structure, and the nature of power flow through the effective channels. In Figures 7 and 8, distributions of the $E_x$-electric fields and pointing vector (Z-component) for broadband excitation are plotted, respectively. From the $E$-field distributions for zero x-length case (Figure 7(a)), it is observed that the $E_x$-field is entirely distributed over the channel; indicating the possibility of strong resonant transmission through the structure. When x-length is increased to 100 and 150 nm (Figure 7(b,c)), the $E_x$-field is distributed over the side channel also, and the strength over the main channel is reduced drastically. This is observed especially for 100 nm.
nm x-length case. The perturbation by the side channel changes the overall impedance of the unit cell circuit which results in this modification in the channel eigen mode. Further increase in the x-length leads to stronger coupling of the side channel. However, the distribution is not the same as observed in the zero x-length case. Here, the field distribution over the main channel becomes non-uniform, especially at the end faces. The distribution of power flow or pointing vector shows a similar trend as presented in Figure 8.

It is observed that the shape anisotropy plays a significant role in determining the resonant optical transmission. Electric field distribution and the nature of power flow clearly demonstrate the shape dependence of the distribution of induced charges and nature of current flow [33]. Shape-dependent change in the capacitive coupling causes the change in the resonant transmission. Further, broadening of FWHM is caused by the plasmonic interaction at the interface of the MDM tri-layer system. Similar transmission properties in MDM sandwich structure having asymmetric holes are observed by Ding et al. [28]. The resonant peak positions are explained on the basis of the effective LC circuit model.

4. Conclusion

Optical transmission through plasmonic MDM tri-layer is investigated using FDTD computation. Shape-dependent resonant optical transmission is studied on the periodic array of anisotropic “T” and “L” shape subwavelength plasmonic structures numerically using FDTD computation. The periodic array of these structures is made either in the single-layer gold film or in MDM (gold-SiO2-gold) tri-layer film. A single resonant transmission peak is clearly seen for the T shape array structure, while two resonant transmission peaks are observed for the L shape structure. The resonant frequencies are determined on the basis of an effective LC circuit model. The presence of plasmon interactions widens the FWHM of resonant transmission peaks. Anisotropic shape-dependent spectral funnelling in T and L shape structures has importance in optical device applications.

Disclosure statement

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