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Plasmonic reflectors and high-Q nano-cavities based on coupled metal-insulator-metal waveguides

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Based on the contra-directional coupling, a composite structure consisting of two coupled metal-insulator-metal (MIM) waveguides is proposed to act as an attractive plasmonic reflector. By introducing a defect into one of the MIM waveguides, we show that such a composite structure can be operated as a plasmonic nanocavity with a high quality factor. Both symmetric and anti-symmetric cavity modes are supported in the plasmonic cavity, and their resonance frequencies can be tuned by controlling the defect width. The present structures could have a significant impact for potential applications such as surface plasmon mirrors, filters and solid-state cavity quantum electrodynamics. Copyright 2012 Author(s). This article is distributed under a Creative Commons Attribution 3.0 Unported License.

Surface plasmon polaritons (SPPs) have been suggested to act as novel digital data carriers in information processing, because plasmonics offers both the compactness of electronics and the speed of optics. Over the past years, various plasmonic waveguide structures such as metallic stripes, metal-insulator-metal (MIM) and insulator-metal-insulator (IMI) structures, dielectric-loaded SPP waveguides, and V-shaped metal grooves, have been prototyped as interconnects for information transport. These plasmonic waveguide structures with delicate designs can be further developed to control SPPs beams, and thus to accomplish various functions. As one of the very basic and important devices used to steer SPPs beams in plasmonic circuits, distributed Bragg reflectors (DBRs) have been widely studied both theoretically and experimentally due to its ability to stop SPP propagation within the plasmonic band-gap, and its potential applications in SPP mirrors, wavelength selective components, and plasmonic cavities. These plasmonic DBRs are conventionally realized by periodically varying structural parameters of plasmonic waveguides to obtain a periodic variation in the effective refractive index in the guide. To achieve a well-defined Bragg reflection or extinction in transmission, DBRs should have more than several tens of periods, which makes the devices based on the DBRs very long (at least several micrometers) and requires considerable effort to fabricate.

It has been suggested that when left-handed medium is applied to the waveguiding systems, backward modes with antiparallel energy and phase flows can be supported by waveguides containing left-handed medium. By combining a left-handed medium waveguide and a conventional positive-index-medium waveguide, the contra-directional coupling based on backward modes can be achieved. The corresponding exponential attenuation along the coupled waveguides indicates a rapid coupling rate, therefore leading to very short coupling lengths, which is completely different from that of a coupled conventional waveguide system. This feature has already been applied for the realization of the short couplers consisting of a forward transmission-line edge-coupled to a left-handed (backward) transmission-line in the microwave regime. Recently, the concept of contra-directional coupling has been extended to the optical domain using dielectric materials.
The GaAs-MIM waveguides. The permittivity of silver is evaluated from a Drude model 
photonic crystals\cite{30,31} or plasmonic films.\cite{32} For example, the contra-directional coupling between a 
two-dimensional dielectric photonic crystal waveguide and an optical fiber has been demonstrated 
with high efficiency, in which the backward-wave propagation is feasible at higher bands of the 
photonic crystals.\cite{30} This type of contra-directional coupling based on backward modes offers a new 
possibility in the design of optical components and circuits, such as ultra-short couplers, plasmonic 
splitters, and waveguide cross-over components.\cite{32–34}

In this paper, the guiding SPP modes including the magnetic field-symmetric and anti-symmetric 
 modes are first investigated for the MIM structures with different insulator thicknesses. The contra-
directional coupling between the symmetric and anti-symmetric modes is demonstrated in the 
coupled MIM waveguides, in which the effect of the separation between two MIM waveguides is 
discussed in detail. Based on the principle of contra-directional coupling, a composite structure with 
a much simple design is proposed to act as an attractive plasmonic reflector. Furthermore, it is shown 
that high-Q plasmonic nanocavities can be realized based on such composite MIM waveguide by 
introducing a defect into one of the MIM waveguides. Both symmetric and anti-symmetric cavity 
 modes can be supported in the plasmonic cavities, and their resonance frequencies can be tuned 
efficiently by controlling the defect width.

In a MIM structure, the SPPs at two metal-dielectric interfaces can be coupled to each other 
to form a magnetic-field symmetric mode below the SPP resonance frequency and a magnetic-field 
anti-symmetric mode above the SPP resonance frequency.\cite{35} The field symmetric mode (denoted 
as s-mode) is a conventional forward propagation plasmon mode, and is mostly used as guiding 
 modes in MIM plasmonic waveguides.\cite{4,5,7} In contrast with the symmetric mode, the field anti-
symmetric mode (denoted as a-mode) has antiparallel group and phase velocities, and actually is 
a backward propagation plasmon mode, which has been employed in an ultrathin MIM waveguide 
to experimentally realize a two-dimensional negative-index material in the visible regime.\cite{36} As 
mentioned above, contra-directional coupling can be achieved between a waveguide sustaining 
backward modes and a waveguide supporting forward modes.\cite{24–29} In the meanwhile, the MIM 
structure can guide both forward s-mode and backward a-mode. This makes the MIM waveguide 
structure a promising candidate for the realization of contra-directional coupling.\cite{34} However, for 
the MIM structures with same dielectric material the s-mode and a-mode are separated by the 
SPP resonance frequency, and thus reside in different frequency bands.\cite{35} Since the SPP resonance 
frequency decreases with increasing the relative electric permittivity of the dielectric media adjacent 
to metals,\cite{1} the approach of stacking MIM structures consisting of different dielectrics renders the 
possibility of producing both forward and backward modes at the same frequency.\cite{34} For this reason, 
we introduced magnesium fluoride (MgF\textsubscript{2}, dielectric constant \(\varepsilon_{\text{MgF}_2} = 1.69\)) and gallium arsenide 
(GaAs, dielectric constant \(\varepsilon_{\text{GaAs}} = 12.25\)) into our proposed composite MIM structures as two 
insulators.

The frequency dependent complex propagation constant \(\xi = \beta + i\alpha\) with \(\alpha\) and \(\beta\) being the 
attenuation constant and phase constant is first conducted for the isolated Ag-MgF\textsubscript{2}-Ag and 
Ag-GaAs-Ag structures using the mode analysis solver of a commercial finite-element-method 
software package (COMSOL Multiphysics). The effective index \((N_{\text{eff}})\) is defined as 
\(N_{\text{eff}} = \beta/k_0\), and the propagation length \((L_{\text{prop}})\) is defined as 
\(L_{\text{prop}} = 1/(2\alpha)\), where \(k_0\) is the vacuum wave vector. In the calculations, three different 
insulator thicknesses \(d = 50\) nm, \(30\) nm, and \(20\) nm are chosen for the MgF\textsubscript{2}-MIM waveguides, and three typical 
thicknesses \(t = 20\) nm, \(15\) nm, and \(10\) nm are chosen for the GaAs-MIM waveguides. The permittivity of silver is evaluated from a Drude model 
\(\varepsilon_{\text{metal}} = \varepsilon_{\infty} - \omega_p^2/(\omega^2 + i\omega\gamma)\) with background dielectric constant \(\varepsilon_{\infty} = 3.7\), plasma frequency \(\omega_p = 1.38 \times 10^{16}\) 
rad/s, and damping constant \(\gamma_0 = 2.73 \times 10^{13}\) rad/s.\cite{37} It is known that for a planar interface between 
dielectric (dielectric constant \(\varepsilon_j\)) and silver the SPP resonance frequency can be analytically obtained 
from the equation \(\omega_{\text{SP}} = \omega_p[(\varepsilon_{\infty} + \varepsilon_j)^{1/2}]\), when the damping constant is negligible compared to 
the plasma frequency.\cite{1} This equation gives \(\omega_{\text{SP, GaAs}} = 0.2504\omega_p\) and \(\omega_{\text{SP, MgF}_2} = 0.4307\omega_p\) for the 
Ag-GaAs and Ag-MgF\textsubscript{2} interfaces, respectively. As already stated above, within the frequency range 
from \(\omega_{\text{SP, GaAs}}\) to \(\omega_{\text{SP, MgF}_2}\) the MgF\textsubscript{2}-MIM and GaAs-MIM waveguides are expected to support the 
s-mode and a-mode, respectively. In what follows, we restrict ourselves to this frequency range of 
interest. As shown in Fig. 1(a), the dispersion curves of the s-mode in the MgF\textsubscript{2}-MIM waveguides 
(solid lines) have a positive slope for all three different insulator thicknesses, which implies the nature
FIG. 1. (Color online) (a) Dispersion relations of the isolated Ag-MgF$_2$-Ag (solid lines) and Ag-GaAs-Ag (dashed lines) waveguides with different insulator thicknesses. (b) and (c) Normalized magnetic field $z$-component ($H_z$) distributions at a frequency of $\omega = 0.337\omega_p$ for the eigen modes supported by the MgF$_2$-MIM and GaAs-MIM waveguides. The thickness of the MgF$_2$ and GaAs insulator layers is assumed to be $d = 30$ nm and $t = 15$ nm, respectively. (d) and (e) The propagation length of the field symmetric and anti-symmetric modes in the MIM waveguides with different insulator thicknesses.

of the forward mode. In contrast, the dispersion curves of the s-mode in the GaAs-MIM waveguides (dashed lines) exhibit a negative slope, meaning that the energy and phase fronts propagate in opposite directions. To visualize the characteristics of these two eigen modes, the magnetic field $z$-component ($H_z$) distributions are calculated at the frequency of $\omega = 0.337\omega_p$ and shown in Figs. 1(b) and 1(c) for the MgF$_2$-MIM ($d = 30$ nm) and GaAs-MIM ($t = 15$ nm) waveguides, respectively. It is clearly seen that the plasmon mode supported by the MgF$_2$-MIM waveguide indeed has a symmetric magnetic field distribution, whereas an anti-symmetry field distribution is observed for the plasmon mode in the GaAs-MIM structure.

More importantly, we can see from Fig. 1(a) that the s-mode and a-mode are co-existed within the same frequency bands, and their dispersion curves always cross over each other at a certain frequency, which makes a strong coupling between these two modes possible. With increasing the insulator thickness, the s-mode dispersion curves are observed to approach its horizontal asymptote ($\omega_{SP,MgF_2}$) more slowly, while the a-mode dispersion curves approach its horizontal asymptote ($\omega_{SP,GaAs}$) more fast. Since the dispersion curves highly depend on the insulator thickness, the intersection point of two dispersion curves can be tuned to a desired frequency by varying the thickness of the GaAs or MgF$_2$ layer. Meanwhile, the propagation lengths of the s-mode and a-mode are plotted as a function of the operation frequency for the MgF$_2$-MIM and GaAs-MIM waveguides with different insulator thicknesses in Fig. 1(d) and 1(e), respectively. For the s-mode supported by the MgF$_2$-MIM waveguide, the propagation length is observed to monotonically decrease with increasing the operation frequency [Fig. 1(d)]. A different situation is found for the a-mode supported by the GaAs-MIM waveguide. As shown in Fig. 1(e), the propagation length generally increases with increasing the frequency. When the operation frequency is very close to its cut-off frequency (the effective index approaches to $N_{eff} = 1.0$), a transition will occur from quasi-bound a-modes to radiative modes, resulting in a local maximum in the propagation length for the GaAs-MIM waveguides. Furthermore, comparing the propagation lengths of plasmon modes
FIG. 2. (Color online) (a) Dispersion relations of the composite MIM structures with different thicknesses of the silver layer between MgF$_2$ and GaAs. Solid lines with symbols represent a contra-directional and strong coupling regime. Solid lines represent co-directional and weak coupling regimes. Dashed and dot-dashed lines are the dispersion curves of the isolated 30nm-MgF$_2$-MIM and 15nm-GaAs-MIM waveguides, respectively. Inset schematically shows the composite MIM structure formed by stacking the MgF$_2$-MIM and GaAs-MIM waveguides together. (b) Attenuation constant of the composite MIM structures for different values of $s$.

supported by the MgF$_2$-MIM and GaAs-MIM waveguides with different insulator thicknesses, it is seen that both the s-mode and a-mode have a longer propagation length for a larger insulator thickness.

When the individual MgF$_2$-MIM and GaAs-MIM waveguides are stacked together, as schematically shown in the inset of Fig. 2(a), the contra-directional coupling between the a-mode (backward mode) and s-mode (forward mode) is expected to occur around the intersection of their dispersion curves. As an illustrative example, the thickness of the MgF$_2$ and GaAs insulator layer is assumed to be $d = 30$ nm and $t = 15$ nm, respectively. In this case, the dispersion curves for the 30nm-MgF$_2$-MIM and 15nm-GaAs-MIM waveguides [two red curves shown in Fig. 1(a)] are observed to intersect at $\omega \approx 0.34\omega_p$, which is close to the center of the frequency range of interest ($\omega_{sp,GaAs} < \omega < \omega_{sp,MgF_2}$). At this central frequency, a balance between the propagation lengths for the s-mode and a-mode could be achieved, since they have opposite dependencies on the operation frequency [Fig. 1(d) and 1(e)]. It should be noted that the choice of $d = 30$ nm and $t = 15$ nm is somewhat arbitrary. There are many other possible combinations of $d$ and $t$ can be chosen to achieve the same goal, because the dispersion curves highly depend on the insulator thickness [Fig. 1(a)]. The complex propagation constants for the composite MIM structures with different values of $s$ (the thickness of the silver layer between the MgF$_2$ and GaAs) are performed in a similar way as we did for the isolated MIM structures. To acquire more physical insights to the contra-directional coupling, the damping constant in the Drude model has been neglected ($\gamma = 0$).

Figure 2(a) shows the dispersion curves of the composite MIM structures with $s = 15$ nm, 20 nm, and 25 nm. For comparison, the dispersion curves of the isolated 30nm-MgF$_2$-MIM and 15nm-GaAs-MIM waveguides are also plotted in Fig. 2(a). It is seen that around the intersection of the a-mode and s-mode dispersion curves ($\omega \approx 0.34\omega_p$), there is a certain frequency range represented by solid lines with symbols in Fig. 2(a), within which only one phase constant (or effective index) is present for each operation frequency. This clearly indicates the occurrence of the strong contra-directional coupling between the s-mode supported by the MgF$_2$-MIM and the a-mode supported by the GaAs-MIM waveguide. For example, the strong coupling regime for the composite MIM
structure with $s = 20$ nm is from $0.307\omega_p$ to $0.356\omega_p$. Away from this frequency range the dispersion curves of the composite MIM structures [solid lines in Fig. 2(a)] tends to overlap with the dispersion curves of the isolated MIM structures [dashed and dot-dashed lines in Fig. 2(a)], which implies that there exists only weak or negligible coupling. The characteristics of the contra-directional coupling between the MgF$_2$-MIM and GaAs-MIM waveguides could be more clearly seen from the attenuation constants. As shown in Fig. 2(b), a large attenuation is observed for the composite MIM structure in the strong coupling regime. Since no material losses are included in the analysis, the observed attenuation must be purely a result of the coupling effect. It is worth noting that in the contra-directional and strong coupling regime two super-modes exist simultaneously. These two super-modes are a pair of evanescent modes that are decaying in the opposite directions but with the same phase constant. It is evident that within the strong coupling regime two attenuation constants having the same value but opposite sign are observed at each frequency [Fig. 2(b)].

We can also see from Fig. 2 that both the phase and attenuation constants show a dependency on the thickness of the gap silver ($s$) in the composite MIM structure. With decreasing $s$, the entire regime of the contra-directional coupling (or the available operation bandwidth) becomes wider. For example, the available operation bandwidth ($\Delta \omega$) could be extended from $\Delta \omega \approx 0.041\omega_p$ to $\Delta \omega \approx 0.058\omega_p$ when $s$ is decreased from 25 nm to 15 nm. Associated with the widened operation bandwidth, the attenuation constant of the supermodes is observed to be enlarged with decreasing $s$ [Fig. 2(b)]. This means that the contra-directional coupling between the MgF$_2$-MIM and GaAs-MIM waveguides could be achieved more efficiently for smaller value of $s$. Note that with respect to the intersection of the isolated a-mode and s-mode dispersion curves, the maximal attenuation constant of the supermodes is actually red-shifted and the red-shift becomes more evident with decreasing $s$ [Fig. 2(b)]. Although the narrower silver layer between the MgF$_2$ and GaAs could lead to the widened operation bandwidth and enlarged coupling efficiency, it significantly lowers the effective index of the super-modes. As shown in Fig. 2(a), the effective index for a given frequency in the contra-directional coupling regime decreases with decreasing $s$, which implies that the supermodes provide better modal confinement for larger value of $s$. Therefore, there is a trade-off between the mode confinement (effective index) and the coupling efficiency. For this reason, the thickness of the silver layer between the MgF$_2$ and GaAs is assumed to be a moderate value of $s = 20$ nm in our designs.

Now, we are ready to propose a composite MIM structure that operates based on the contra-directional coupling to act as a plasmonic reflector and achieve a SPP stop-band. As depicted in Fig. 3(a), the proposed structure is formed by stacking the MgF$_2$-MIM and GaAs-MIM waveguides together, which is possibly realized with recent developments in fabrication technologies. According to our above analysis, the thicknesses of the MgF$_2$ and GaAs insulator layer, and the silver layer between these two dielectrics are taken as $d = 30$ nm, $t = 15$ nm, and $s = 20$ nm, respectively. The MgF$_2$-MIM waveguide is assumed to be 800 nm long, while the GaAs-MIM waveguide has a finite length $L$ ($L < 800$ nm). Application mode 2D TM In-Plane Harmonic Propagation in COMSOL Multiphysics is used to investigate the SPP guidance characteristic of the proposed structure. Since the contra-directional coupling regime $0.307\omega_p < \omega < 0.356\omega_p$ in our proposed structure is well below $\omega_{SP,MgF2} = 0.4307\omega_p$ (the surface plasmon frequency for the Ag-MgF$_2$ interface), only a forward s-mode is expected to propagate along the MgF$_2$-MIM waveguide. Through launching such an eigen mode from the left input port of the MgF$_2$-MIM waveguide, the transmission and reflection spectra can be retrieved from the $S$-parameter analysis. Note that in the proposed structure, the coupling length is finite and basically equal to the length of the GaAs-MIM waveguide ($L$). The transmission and reflection spectra are first calculated for the proposed structure without loss. As shown in Fig. 3(b), for a 100-nm-long GaAs-MIM waveguide no remarkable stop-band is observed in the transmission spectrum due to the very short coupling length. Upon increasing the GaAs-MIM waveguide length to 200 nm, a stop-band in transmission starts to form around the frequency $\sim 0.332\omega_p$ as a result of the increased coupling efficiency. When the GaAs-MIM waveguide length is increased to 500 nm, a nearly 100% coupling efficiency is already obtained, which results in the formation of a well-defined stop-band in the transmission spectrum and correspondingly a full-reflection region in the reflection spectrum within the frequency range $0.31\omega_p < \omega < 0.355\omega_p$. Strictly speaking, since
FIG. 3. (Color online) (a) Design of a plasmonic reflector by stacking the MgF$_2$-MIM and GaAs-MIM waveguides. (b) Transmission and reflection spectra for different lengths ($L = 100, 200$ and $500$ nm) of the GaAs-MIM waveguides. Note that the damping constant $\gamma = 0$. (c) Red curve indicates magnetic field $H_z$ distribution of the symmetric eigen mode at a frequency of $\omega = 0.332\omega_p$, which is launched from the input port of the MgF$_2$-MIM waveguide. Color map represents $H_z$ distribution in the proposed structure at the frequency of $\omega = 0.332\omega_p$ for $L = 500$ nm.

the coupling efficiency increases with increasing the coupling length, 100% coupling efficiency can only be achieved when the coupling length is infinitely long.$^{31,32}$

To reveal the characteristic features of the stop-band and full-reflection achieved in the proposed structure, magnetic field ($H_z$) distribution in the composite MIM waveguide with $L = 500$ nm is calculated at a frequency of $\omega = 0.332\omega_p$ close to the central frequency of the transmission stop-band. It is seen from Fig. 3(c) that after the input port of the MgF$_2$-MIM waveguide is excited, the eigen mode (s-mode) will first propagate forward along the MgF$_2$-MIM waveguide. When this forward s-mode meets the composite part of the proposed structure (Ag-MgF$_2$-Ag-GaAs-Ag), the evanescent supermodes supported by the composite MIM structure begins to be excited. When the energy flow of the s-mode in the MgF$_2$-MIM waveguide travels along the composite MIM structure far enough, it will be completely transferred to the energy carried by the backward a-mode in the GaAs-MIM waveguide. Therefore, the proposed structure based on the contra-directional coupling provides an immediate return path for the incident energy. As a result, almost all the input energy is guided back to the input-port and no energy exits from the output-port of the MgF$_2$-MIM waveguide, which is similar to the function achieved in conventional DBRs. It is worth noting that due to large attenuation constant of the supermodes the energy transfers from the input s-mode to the a-mode at an exponential rate, which promises a very short coupling length with a high coupling efficiency.

In the above cases, perfect metal (without loss) is used to acquire meaningful physical insights. However, in the practice the realistic metal loss may cause the decline in the performance of the proposed structure. As shown in Fig. 4(a), when the damping constant of $\gamma_0 = 2.73 \times 10^{13}$ rad/s is taken into account, the resultant transmission in the pass bands and reflection in the stop band are found to be diminished. For example, the reflectivity at the central frequency ($\omega = 0.332\omega_p$) of the stop band has dropped from $\sim 100\%$ (for lossless model) to $\sim 80\%$ (for lossy model). To reduce the ohmic loss, we suggest that the proposed structure can either be incorporated with gain materials to compensate$^{38-40}$ or operate at low temperatures.$^{18}$ For convenience sake, a temperature factor $\eta$ is introduced to describe the damping constant at different low temperatures $\gamma' = \gamma_0/\eta$. Note that $\eta = 1.0$ corresponds to the room temperature. It is seen from Fig. 4(b) that with increasing the temperature factor (decreasing the damping constant) the reflectivity at the central frequency of $\omega = 0.332\omega_p$ exponentially increases and tends to 100%. For example, at the operation temperature of
FIG. 4. (Color online) (a) Transmission and reflection spectra for the proposed structure with a 500-nm-long GaAs-MIM waveguide, in which the realistic metal loss (η = 1.0, γ′ = γ/η = 2.73 × 10^{13} \text{ rad/s}) is taken into account. (b) The dependency of the reflectivity at the central frequency of the stop band (ω = 0.332ω_p) on the temperature factor. The damping constant is given by γ′ = γ/η.

FIG. 5. (Color online) (a) Schematic view of a composite MIM structure containing a plasmonic nano-cavity that is constructed by separating the 500-nm-long GaAs-MIM waveguide at its center with a small gap (gap width: g). (b) Transmission spectrum of the structure with a gap width g = 40 nm. The inset shows the enlarged portion around the transmission maximum located at ω = 0.3218ω_p. (c) and (d) Magnetic field (H_z) distributions at ω = 0.3218ω_p and ω = 0.3528ω_p.

40 K, the damping constant of the silver could be decreased by approximately a factor of 25 from its room temperature value. In such a low temperature, the reflectivity has reached 99% very close to the value obtained for the lossless model.

Similar to the cavity formation in photonic crystals where perfect periodicity of the dielectric system is broken by a local defect leading to local defect photonic modes within the forbidden band gap, SPP cavities in conventional plasmonic DBRs can generate localized SPP states in the band gap region, which have been found to exhibit attractive properties in light emission, ultra low-threshold lasers, and cavity quantum electrodynamics applications, etc. Very interestingly, based on the SPPs stop band of our proposed composite MIM structure, a plasmonic nanocavity can be constructed by introducing a defect into the GaAs layer of the composite MIM waveguide. As schematically shown in Fig. 5(a), the nanocavity or defect is formed by separating the 500-nm-long GaAs layer at its center with a small gap (gap width: g). To capture the main physics embodied in our numerical results, the damping constant of silver is firstly neglected. The effect of metal losses will be discussed in the later part. Figure 5(b) presents the transmission spectrum for a defect composite MIM waveguide with g = 40 nm. It is seen that two extremely narrow-band transmission resonances locating at ω = 0.3218ω_p and ω = 0.3528ω_p are observed within the SPPs stop-band 0.31ω_p < ω < 0.355ω_p. These results demonstrate that at these resonances light wave can excite resonant SPP
cavity modes in the nano-cavity with a high transmittance through the composite structure. To clarify the origin of these two resonances, magnetic field ($H_z$) distributions at the corresponding resonant frequencies are calculated and shown in Figs. 5(c) and 5(d). It is seen that the fields are mostly localized within the nano-cavity region and oscillate in a standing-wave-like pattern. In particular for the resonance at $\omega = 0.3218\omega_p$, the magnetic field distribution has a mirror symmetry with respect to the vertical central line of the defect, while a quite different situation is found for the resonance at $\omega = 0.3528\omega_p$, in which the magnetic field is anti-symmetrically distributed [Fig. 5(d)]. Thus, two resonances at $\omega = 0.3218\omega_p$ and $\omega = 0.3528\omega_p$ can be termed as the first-order symmetric and anti-symmetric cavity modes according to their magnetic field distributions, respectively.

In order to evaluate the figure of merit of a resonant cavity in this regard, a key parameter is the cavity quality factor ($Q$), which is defined as a ratio of the central resonance frequency ($\omega_c$) to the full width at half maximum (FWHM) of the SPP cavity mode ($\Delta\omega$). Higher $Q$ indicates a lower rate of the energy escaping from the cavity per cycle of oscillation relative to the energy stored in the cavity at resonance. By using a Lorentz function to fit the transmission peak at $\omega_c = 0.3528\omega_p$, a FWHM $\Delta\omega = 3.2 \times 10^{-4}\omega_p$ is found and a corresponding quality factor $Q = \omega_c/\Delta\omega \approx 1103$ is estimated. It is clearly seen from Fig. 5(b) that the symmetric cavity mode at $\omega_c = 0.3218\omega_p$ is much sharper than that at $\omega = 0.3528\omega_p$, and its quality factor is as high as $Q \approx 4597$ (FWHM $\Delta\omega = 7.0 \times 10^{-5}\omega_p$).

In the following, we will demonstrate that both the resonant frequency and the quality factor of these cavity modes could be tuned by varying the defect width ($g$). As shown in Fig. 6(a), the spectra positions of the transmission maxima are collected for different defect widths. It is directly seen that for the cases with $g < 40$ nm, only a first-order symmetric cavity mode is supported in our proposed plasmonic nanocavity. When the defect width starts from 40 nm, in addition to the first-order symmetric cavity mode plasmonic nanocavity turns to support a first-order anti-symmetric cavity mode. At the same time, it is found that with increasing the defect width, both the symmetric and anti-symmetric first-order cavity modes decrease in frequency. When the defect width is increased to 70 nm, the first-order symmetric cavity mode is almost locating at the stop-band lower-frequency edge. Further increasing the defect width to 80 nm, the first-order symmetric cavity mode moves outside of the stop-band region. On the other hand, a new cavity mode appears in the stop-band
FIG. 7. (Color online) (a) Dependency of quality factors of the first-order symmetric cavity modes upon their resonance frequencies. The radiation $Q$ factor and total $Q$ factor are evaluated for the damping constant $\gamma = 0$ and $\gamma' = 2.028 \times 10^{12}$ rad/s, respectively. (b) Dependency of the total $Q$ factor of the first-order symmetric cavity mode for $g = 40$ nm on the temperature factor. The damping constant is given by $\gamma' = \gamma_0/\eta$.

region when the defect width exceeding 100 nm. As shown in Fig. 6(b), magnetic fields ($H_x$) at the resonance frequency of $0.3502\omega_p$ for $g = 120$ nm are distributed symmetrically with respect to the vertical central line of the defect, in which an additional field node is observed in the cavity region compared to the field distribution shown in Fig. 5(c). Therefore, this new mode can be identified as the second-order symmetric cavity mode.

Figure 7(a) shows the dependency of cavity quality factor on the resonance frequency of the first-order symmetric cavity mode (red line with squares). Maximum quality factor on the order of $10^6$ is observed at the resonance frequencies of $\omega = 0.3151\omega_p$ (the corresponding defect width $g = 57$ nm) and $\omega = 0.3353\omega_p$ ($g = 16$ nm), respectively. Away from these two frequencies the quality factor decreases rapidly. Note that the dependency here is quite different from that in plasmonic cavity based on DBRs in which the maximum $Q$ occurs at the center frequency of band-gap. It should be noted that the quality factor discussed above actually is radiation $Q$ factor ($Q_{\text{rad}}$) because the imaginary part of the permittivity of silver has been neglected in the above discussions. For a plasmonic cavity formed with a realistic metal the absorption quality factor ($Q_{\text{abs}}$) due to the ohmic loss of metal has to be taken into account, and will result in a diminished value of the total quality factor ($Q_{\text{tot}}$), which can be described as $1/Q_{\text{tot}} = 1/Q_{\text{rad}} + 1/Q_{\text{abs}}$. As shown in Fig. 7(b), when the damping constant of $\gamma_0 = 2.73 \times 10^{13}$ rad/s ($\eta = 1$) is taken into account, the total quality factor of the first-order cavity mode for the defect width $g = 40$ nm ($\omega = 0.3218\omega_p$) is degraded from $Q_{\text{rad}} \approx 4597$ (for lossless model) to $Q_{\text{tot}} \approx 200$ (for lossy model). To improve the total quality factor, we suggest that the proposed structure can operate at low temperatures. It is seen from Fig. 7(b) that with increasing the temperature factor (decreasing the damping constant) the total quality factor for $g = 40$ nm continuously increases and can reach a value of $Q_{\text{tot}} \approx 2438$ at the operation temperature of 40 K ($\eta = 25$). In addition, we used the damping constant of $\gamma' = 2.028 \times 10^{12}$ rad/s to simulate a low temperature condition (temperature factor $\eta \approx 13$), and calculated total quality factors of first-order cavity modes supported by the plasmonic cavities with different defect widths. In such a low temperature, the total quality factor is evaluated to be on the order of $10^3$ [Fig. 7(a) (blue line with circles)].

In conclusion, based on the contra-directional coupling mechanism, a composite structure with a simple design consisting of MgF$_2$-MIM and GaAs-MIM waveguides has been proposed to achieve the function of plasmonic Bragg reflectors. By introducing a defect into the MgF$_2$-MIM waveguide, a plasmonic nanocavity is further realized and demonstrated to support both symmetric and anti-symmetric cavity modes, and their resonance frequencies can be tuned by controlling the defect width. The dependency of quality factors upon the resonance frequency is also investigated for the first-order symmetric cavity modes. Two maximum radiation quality factors on the order of $10^6$ have been achieved. Our results could have a significant impact for potential applications such as SPP-based mirrors, filters, and solid-state cavity quantum electrodynamics.
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