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Enhanced interaction strength for a square plasmon resonator embedded in a photonic crystal nanobeam cavity

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Abstract. The deployment of nanocavities may efficiently enhance the light-matter interaction for photonic components on chip. Three nanoscale cavity designs are investigated, including the one-dimensional (1-D) photonic crystal (PhC) nanobeam cavity, inline waveguide-integrated plasmon cavity, and square plasmon resonator embedded in the 1-D PhC nanobeam cavity (i.e., Combo cavity). The cavity performance, such as quality and Purcell factor, mode volume, and light-matter interaction strength, are evaluated for each structure for comparison. A deep subwavelength mode volume of $0.18 \left(\frac{\lambda}{2n}\right)^3$ is observed in the Combo cavity, which exhibits an improved Purcell factor up to 428 and a 44 times enhanced interaction strength due to the compressed mode volume compared to the inline plasmon cavity. Thus, the Combo cavity shows promise of becoming a potential building block for active components of next-generation on-chip photonic circuits. © 2015 Society of Photo-Optical Instrumentation Engineers (SPIE) [DOI: 10.1117/1.JNP.9.XXXXXX]

Keywords: photonic crystals; resonant cavity; plasmon; mode volume.

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1 Introduction

Emerging on-chip photonics serves as a potential solution for creating a continuing path of development for optical interconnects.1,2 Resonant cavities based optical devices allow for a variety of advantages (i.e., long photon lifetime and strong mode confinement) for next-generation photonic integrated circuits. Fundamentally, the interaction strength of the light with matter is given by the product of the electric field density times the number of available modes per unit frequency (i.e., optical density of states), which is derived from Fermi’s Golden rule. This light-matter interaction (LMI) strength can be quantified by a factor proportional to $Q/V_{\text{mode}}$, (where $Q$ is the cavity quality factor and $V_{\text{mode}}$ is the effective volume of the electromagnetic energy of a resonant mode) and, thus, is proportional to the Purcell factor.3 Physically, this factor relates the energy stored (i.e., optical loss) with the optical density of states, which increases the interaction probability of photons, such as with a two-level system. However, active optoelectronic devices rely often on optical nonlinear effects that strengthen the polarization due to the enhanced electric fields (i.e., $\sim|E|^2$ and $\sim|E|^3$ for second- and third-order effects). Therefore, a nanoscale cavity’s device relevance is given by the factor proportional to $Q/V_{\text{mode}}$ times the field density, as we will discuss below. Technologically, the deployment of LMI-enhanced optical cavities allows for efficient active devices, such as light sources and electro-optic modulators. Many high $Q$-factor optical cavities with small mode volumes have been developed and fabricated. Among them, the three most predominant types are categorized, including Fabry-Perot micro-post cavities,4 whispering gallery mode cavities,5 and photonic crystal (PhC) cavities.6–8 Here, we show that the combination of one-dimensional (1-D) PhC microcavities in conjunction with...
two-dimensional (2-D) plasmonic confinement outperforms diffraction-limited PhC cavities and plasmon cavities alike.

1-D PhC microcavities embedded in a narrow photonic wire waveguide (i.e., nanobeam cavity) have been widely investigated.9–11 Such cavities offer optical confinement by PhC mirrors (i.e., Bragg mirrors) along the waveguide direction and through total internal reflections in the transverse directions. A confined mode usually forms a hotspot around the center of the cavity. Engineering of active gain materials in the cavity may pave the way for achieving nanolasers with subwavelength mode volumes through enhanced LMI. Recently an electrically driven, 1-D PhC nanobeam laser with a $0.35(\lambda/n)^3$ mode volume has been demonstrated at a lasing wavelength of 1578 nm.12

Plasmonics (i.e., metal-optics) is an emerging branch of technology and has been researched extensively in the last decade.13 Surface plasmon polaritons (SPP), collective oscillations of electronic charges at metal-dielectric interfaces, can be utilized for future optoelectronic devices. SPPs on an infinite metal/dielectric interface may provide confinement only in the direction perpendicular to the interface. The contrast in the mode effective index of SPP at the metal/dielectric/air interface and metal/air interface results in the lateral confinement. Taking advantage of the feature of SPP, various plasmon-based cavities are reported.14–16 Moreover, sub-diffraction-limited laser sources have been demonstrated utilizing plasmonic confinement.17–19 For instance, hybrid metal-insulator-semiconductor based cavity consisting of an Ag-MgF$_2$-CdS stack on a quartz substrate20,21 allows for sub-diffraction-limited tight optical confinement (i.e., $\lambda/20$), due to the enhanced density-of-states and allows for nanoscale lasers operating at room temperature. Combining plasmonic with a PhC structure, a so-called plasmonic crystal defect nanolaser is formed by InGaAsP/InP 1-D PhC nanobeam cavity on a gold metal film.22 This laser benefits from a small mode volume with $0.3(\lambda/n)^3$ at a $\lambda = 1342$ nm wavelength, which is 10 times smaller than a similar mode in a PhC of the same physical dimensions.

Here, we combine a square plasmon resonator embedded in a 1-D PhC nanobeam cavity (i.e., Combo cavity) for further compressing its mode volume in deep subwavelength scales. This leads to an increased Purcell factor and enhanced interaction strength between light and matter. The performance of three nanocavity designs are numerically investigated and compared, including the 1-D PhC nanobeam cavity, the inline waveguide-integrated plasmon cavity, and the Combo cavity. By using a finite-difference time-domain (FDTD) simulation method, the mode profile for each cavity structure is recorded, and the corresponding $Q$-factor and Purcell factor are obtained. A result is that the interaction strength of the Combo cavity outperforms the other two cavity structures due to the miniscule mode volume originating from both plasmonic and PhC confinement effects. These resonant cavities, thus, show potential as building blocks for creating next-generation on-chip light-emitting devices.

2 Cavity Design

2.1 1-D PhC Nanobeam Cavity

The design process of a 1-D PhC nanobeam cavity usually consists of engineering three elements: (1) the PhC mirror, (2) the taper, and (3) the cavity length. Such a process can be found everywhere in the literature.23,24 The ultrahigh $Q$ value in a nanobeam cavity depends strongly on a precise cavity length due to the dependence of the scattering loss on the length.25 This phenomenon is consistent with the effect for satisfying the resonance condition of a Fabry-Perot cavity in principle. In order to obtain a high-$Q$ nanobeam cavity, the cavity length is usually as short as tens of nanometers.9,11,25

A photonic ridge waveguide with the cross-section of height 340 nm and width 400 nm supporting a transverse-electric (TE) mode is first determined on an Si$_3$N$_4$/SiO$_2$ substrate. In order to embed a plasmon island resonator inside the 1-D PhC nanobeam cavity, the cavity length (i.e., $L = 260$ nm) is at least larger than the square size of the resonator. Such a long cavity length usually degenerates the $Q$-factor of the 1-D PhC nanobeam cavity by several orders of magnitude if simply extending $L$ while keeping the other parameters unchanged. With the air of producing a long cavity length with a reasonable $Q$ value cavity, the PhC mirror and the taper
parameters, including the hole period \( a \), hole radius \( r \), minimum hole spacing in the taper section \( a_{\text{min}} \), and number of taper and mirror pairs \((n, m)\), are optimized. This design is performed by using commercially available three-dimensional (3-D) FDTD software (Lumerical Solutions, Inc). Since the periodicity of the holes is related to a center wavelength of the stop-band, the hole spacing \( a = 250 \) nm is selected for a target wavelength of \( \sim 850 \) nm according to \( a = \lambda_o/2n_{\text{eff}} \), where \( n_{\text{eff}} \) is the effective mode index of the cavity (\( n_{\text{eff}} = 1.7 \) is simulated for our case). For the taper section, a 12-hole linear taper with a minimum hole spacing \( a_{\text{min}} = 160 \) nm is given for minimizing the reflection loss from the incident lowest-order waveguide mode. The other design parameters are listed in the caption of Fig. 1(a).

There are two types of \( Q \)-factor calculations (i.e., low \( Q \) cavity and high \( Q \) cavity) used in this work. The \( Q \)-factor for a low \( Q \) cavity is determined through the Fourier transform of a field by finding the resonance frequencies \( f_R \) of the signal and measuring the full width half maximum (FWHM, \( \Delta f \)) of the resonant peaks, i.e., \( Q = f_R/\Delta f \), if the electromagnetic fields decay completely from the simulation in a time that can be reasonably simulated by FDTD. Otherwise, the \( Q \)-factor for a high \( Q \) cavity cannot be determined from the frequency spectrum because the FWHM of each resonance in the spectrum is limited by the time of simulation. In this case, the \( Q \)-factor is calculated from a slope of the envelope of a decaying signal using the equation

\[
Q = \frac{-2\pi f_R \log_{10} e}{2m},
\]

where \( m \) is the slope of the logarithm of the time signal envelope. As the cavity length (i.e., \( L \)) is sensitive to the \( Q \)-factor, \( L \) is swept to study both the variation of \( Q \)-factors and the shifting property of resonance wavelengths by using the high \( Q \) calculation method (Fig. 2). As expected, the resonant wavelength is redshifted due to the increased effective index of the cavity dependence on the longer \( L \). A minimum \( Q \) value of \( \sim 7000 \) is observed for a wide range of cavity lengths (i.e., 80 to 320 nm), and a high value of \( Q \approx 24,000 \) is found as \( L = 120 \) nm.

### 2.2 Inline Plasmon Cavity

Taking advantage of the dielectric-loaded SPP waveguide concept, a plasmon resonant cavity can be formed. Here, a square \( \text{Al}_{0.3}\text{Ga}_{0.7}\text{As} \) (20 nm)-GaAs quantum well (QW, 300 nm)-\( \text{Al}_{0.3}\text{Ga}_{0.7}\text{As} \) (20 nm) stack is sandwiched between a square Au metal pad on top and an \( \text{SiO}_2 \) buffer layer [Fig. 1(b)]. Aiming toward an efficient waveguide coupling from the plasmon cavity, this cavity is inserted into a conventional photonic wire waveguide made of \( \text{Al}_{0.3}\text{Ga}_{0.7}\text{As} \) material in the \( x \) direction, forming an inline waveguide-integrated plasmon cavity. The structure may provide sub-diffraction-limited mode confinement through total internal reflection of the surface plasmons at the cavity boundaries. The cavity geometry with the

![Fig. 1 Schematic of (a) one-dimensional (1-D) photonic crystal (PhC) nanobeam cavity with air holes, and cavity length, \( L = 260 \) nm; hole period of mirror section, \( a = 250 \) nm; minimum hole distance of taper section, \( a_{\text{min}} = 160 \) nm; hole radius, \( r = 0.18a \); number of taper hole pairs, \( n = 12 \); number of mirror hole pairs, \( m = 16 \); waveguide height, \( h = 340 \) nm. (b) Inline resonant cavity with square size, \( w = 250 \) nm, cavity height, \( H = 340 \) nm, Au layer thickness = 100 nm. (c) Combo cavity, namely, a square plasmon cavity by cutting the semiconductor nanowire waveguide [Fig. 1(b)] in the light propagation direction is embedded inside the PhC nanobeam cavity. The input of complex refractive indices (i.e., \( n \) and \( \kappa \)) are from the Lumerical built-in material database.](image-url)
cross-section in the $xz$ direction is schematically shown in Fig. 1(b), where the GaAs QW region consists of a periodic structure with undoped $\text{Al}_{0.3}\text{Ga}_{0.7}\text{As}$ barrier (i.e., 10 nm) and GaAs well (i.e., 7 nm) layers. The cavity width is 250 nm long, and the height is 340 nm, to purposely match the height of the 1-D PhC nanobeam cavity.

2.3 Combo Cavity

The Combo cavity is constructed with a square plasmon cavity embedded at the center of the 1-D PhC nanobeam cavity [Fig. 1(c)]. The square plasmon cavity is made through cutting the semiconductor nanowire waveguide on both sides [Fig. 1(b)] in the light propagation direction. The $Q$ simulation is repeated with the Combo cavity; however, the low $Q$ calculation method is used for accurate results.

3 Results and Discussions

The cavity mode for each structure is excited by placing an electric dipole source with $z$-orientation inside the corresponding cavity. The 1-D PhC nanobeam cavity exhibits a transverse-magnetic (TM)-like fundamental mode (i.e., the $E$ field in the $z$ direction is dominant) [Fig. 3(a)]. The electric field of the TM mode extends longitudinally along the waveguide, which is consistent with free-standing dual-polarized silicon PhC nanobeam cavities. In addition, the electric field profile is confined in the high index material between these air holes, which is expected for this type of structure enhancing LMI.

Since surface plasmon waves exist only in the direction perpendicular to the metal/dielectric interface, a $z$-oriented dipole source close to the edge is used to excite a TM-polarized cavity mode between the Au metal pad and the GaAs QW gain medium. A square-shaped plasmon cavity is formed in the region covered by the Au pad due to the high effective index contrast between the SPP mode and the surroundings. The electric field is confined along the boundaries of the cavity (i.e., triple bounded interface with air, Au and GaAs) through total internal reflection [Fig. 3(b)], and the mode is labeled as $\text{TM}(p, p, q)$ [i.e., $\text{TM}(1, 1, 1)$ for our case], where $p$ and $q$ represent the mode numbers associated with the width ($W$) and height ($H$) of the cavity, respectively. The mode confinement potentially leads to the necessary cavity feedback to resonate for lasing, if optically or electrically pumping the gain medium. The in-plane electric fields efficiently coupled to a TE mode of the $\text{Al}_{0.3}\text{Ga}_{0.7}\text{As}$ semiconductor waveguide is also observed, exhibiting the strong mode coupling between this photonic waveguide and the plasmon cavity mode [Fig. 3(b)]. Importantly, our simulations show that $\sim60\%$ of the radiated energy from the plasmon cavity with a thickness $>260$ nm can be efficiently coupled to the neighboring waveguides. Similarly, a $z$-oriented dipole source is placed at the center of the Combo cavity due to the $z$-direction polarization-preferred square plasmon cavity. Interestingly, the particular electric field with four hotspots (originally shown from the square plasmon cavity without any
waveguides) located in the center of the Combo cavity indicates the aforementioned cavity in the xy plane [Fig. 3(c)]. This strong mode confinement from the dual cavities can be utilized for enhancing the LMIs as we discuss next.

In recent years, the Purcell factor, \( F_p \), has been used to describe the LMI in laser physics as it relates to a measure of the spontaneous emission rate enhancement of a dipole emitter source placed in the cavity with respect to that in a homogeneous semiconductor material. An equation widely used for the evaluation of \( F_p \) is given by

\[
F_p = \frac{3}{4\pi^2} \left( \frac{\lambda_R}{n} \right)^3 \left( \frac{Q}{V_{\text{mode}}} \right),
\]

where \( \lambda_R \) is the resonant free-space wavelength of the cavity, \( n \) is the real part of the material complex refractive index at the field antinode, and \( V_{\text{mode}} \) is estimated from a commonly used definition:

\[
V_{\text{mode}} = \frac{\int |E(r)|^2 dV}{\max[|E(r)|^2]},
\]

(2)

where

(3)

Fig. 3 Electric field distribution profiles of cavity modes for three cavity structures, respectively. (a) TM-like fundamental mode of 1-D PhC nanobeam cavity, and \( E_{xy} \) is recorded in the xy plane at the cavity center along the z direction. (b) Dielectric-loaded surface plasmon polaritons mode [i.e., TM \( (1, 1, 1) \)] of the inline waveguide-integrated plasmon cavity, and \( E_{xy} \) is recorded at the z direction 80 nm away from the Au/Al\(_{0.3}\)Ga\(_{0.7}\)As interface. The surface plasmon effect creates a local cavity in the square region (i.e., the region covered by the Au pad) by total internal surface plasmon reflection, which could be utilized in, e.g., laser devices. The cavity’s radiative light is predominantly coupled into the neighboring Al\(_{0.3}\)Ga\(_{0.7}\)As waveguides on both directions. (c) TM-like cavity mode of the Combo cavity (i.e., square plasmon island resonator embedded in the PhC nanobeam cavity), and \( E_{xy} \) is recorded in the xy plane at the Combo cavity center along the z direction. \( E_{xz} \) for all the three structures are recorded in the xz plane along the \( y = 0 \) direction.

Not sure which one is the fourth part label? To make it clear, we may revise this sentence by, Exz is recorded in the xz plane along the y=0 direction for all the three structures, respectively.
where \( \varepsilon \) is the dielectric constant, \( E(r) \) is the electric field strength, and \( V \) is a quantization volume encompassing the resonator and with a boundary in the radiation zone of the cavity. Equation (2) indicates that a large \( Q \) and a smaller \( V_{\text{mode}} \) are desired for an enhanced spontaneous emission rate (i.e., \( F_p \)) that is proportional to \( Q/V_{\text{mode}} \). Here, the normalized mode volume \( V_n \) is introduced by \( V_{\text{mode}} \) normalized to \( (\lambda/2n)^3 \) (i.e., typically referred to as the diffraction-limited volume in a cubic half-wavelength in material), namely, \( V_n = V_{\text{mode}}/(\lambda/2n)^3 \). \( V_n \) for the 1-D PhC nanobeam cavity is far larger than that in the two other cavity cases (Table 1). Using the Combo cavity, a rather small \( V_n \) can be achieved due to the sub-wavelength scale mode volume enabled by surface plasmons in the double-cavity. This Combo cavity structure may provide a potential solution for an on-chip nanoscale laser source.

Utilizing Eq. (2), \( F_p \) can be estimated if \( Q \) and \( V_{\text{mode}} \) are both known parameters. Using the high \( Q \) calculation method, a \( Q \)-factor of \( \sim 10,000 \) is obtained at a wavelength of 824 nm for the 1-D PhC nanobeam cavity (Fig. 2). The \( Q \)-factors of 17.3 and 126 are simulated by the low \( Q \) calculation method for the inline plasmon cavity and the Combo cavity, respectively. Particularly for the inline plasmon cavity, the low cavity \( Q \) may result from its mode TM (1, 1, 1) suffering both energy scattering from the cavity boundaries and partially coupling into the waveguides, as well as a larger plasmonic loss with metal. The corresponding values of \( F_p \) are 626, 14, and 428 for the three cavity structures, respectively (Fig. 4). Although the Purcell factor in the Combo cavity is lower relative to the photonic crystal nanobeam (PCNB) cavity, the interaction strength (i.e., \( |E|_{\text{max}}^2 \times F_p \)) is strongest for the Combo cavity. For the interaction strength of third-order effects (i.e., \( |E|_{\text{max}}^3 \times F_p \)), the numbers of 348, 38, and 2103 are achieved for the PCNB, Inline, and Combo cavities, respectively. We can see that the LMIs of the 2-D confined SPPs may be enhanced by introducing an external cavity, where the interference between multiple reflections within the cavity may substantially modify the intrinsic density of the states.

There are two ways to increase the Purcell factor according to Eq. (2). The classical approach is to enhance the cavity \( Q \)-factor. However, this is rather unpractical since it not only requires

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<th>Structure</th>
<th>Photonic crystal nanobeam cavity</th>
<th>Inline plasmon cavity</th>
<th>Combo cavity</th>
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<tr>
<td>( \lambda_{\text{Resonance}} ) (nm)</td>
<td>824</td>
<td>855</td>
<td>842</td>
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<tr>
<td>( V_n (\lambda/2n)^3 )</td>
<td>9.7</td>
<td>0.75</td>
<td>0.18</td>
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Table 1 Comparison of resonant wavelength and normalized mode volume for three cavity structures.
increased wafer space, but also has negative effects for data communication applications, particularly for lasers driven in a direct modulation mode due to the long cavity photon lifetimes inside the high $Q$ cavity, $\tau_{ph} = (Q\lambda)/(2\pi c)$, where $\lambda$ is the operating resonant wavelength and $c$ is the speed of light in vacuum. The second possible approach is to decrease the normalized mode volume, $V_n$ (Table 1). Since $Q$ is ultimately limited in practice by other factors, such as bandwidth considerations, material absorption, or fabrication tolerance, minimizing $V_n$ for a given $Q$ is usually a preferred solution. In this work, we show that deep subwavelength mode volumes may possibly be realized by incorporating a plasmon resonator in another cavity forming a Combo cavity. In terms of a nano light-emitting device application, the benefit of using plasmonic-based optical cavities potentially enables spontaneous emission rates that are faster than the stimulated emission rates. Note, this is not limited to nanoscale-based laser cavities but is applied to conventional laser designs as well.\(^{33}\) On the other hand, the internal dynamics leading toward the laser threshold are more efficiently utilized when a smaller optical mode volume is used (i.e., higher $F_p$ and spontaneous emission coupling factor, $\beta$). The case with a smaller mode volume often translates into a low power requirement. In addition, the energy per bit of a charge-based device (e.g., electro-optic modulator) is proportional to the total accumulated charge, $Q_{charge}$, times the applied drive voltage, $V_D$ [Eq. (4)]. Borrowing the example for a free-carrier-based modulator,\(^{32}\) this power efficiency is proportional to the optical mode cross-sectional area divided by the device cavity’s finesse, $\mathcal{F}$, based on the equation

$$E_{\text{bit}} = \frac{1}{2} C V_D^2 = \frac{1}{2} V_D Q_{charge} \propto \frac{A_{\text{mode}}}{\mathcal{F}} \propto \frac{1}{F_p} \propto \frac{V_{\text{mode}}}{Q},$$

(4)

where $E_{\text{bit}}$ is the energy per bit, $C$ is the device capacitance, $V_D$ is the drive voltage, $Q_{charge}$ is the total accumulated charge, $A_{\text{mode}}$ is the effective position-dependent cross-sectional area of the optical mode, and $\mathcal{F} = \Delta F_{\text{FSR}}/\Delta F_{\text{FWHM}}$, where $\Delta F_{\text{FSR}}$ is the free spectral range (FSR) and $\Delta F_{\text{FWHM}}$ is the resonant peak’s linewidth. Furthermore, Eq. (4) indicates the fact that waveguide-based devices with a higher 3-D optical confinement (i.e., small $V_{\text{mode}}$) also allow for low driving power consumption. In a recent study, Lin et al. found a fundamental tradeoff between the energy per bit and the 3-dB rolloff modulation speed of electro-optical modulators.\(^{33}\) This tradeoff is independent of the cavity $Q$-factor and proportional to the data bandwidth squared. However, these results were derived for photonic cavities with diffraction-limited optical confinement. Future research should investigate these limits for plasmonic cavities with varying optical confinement dimensionalities.

Nonetheless, a fundamental drawback of plasmonic cavities can be the insertion loss associated with the ohmic losses of the utilized metal. We investigate the transmission through the cavity at a spectral distance 1/2 FSR away from the resonance for the two plasmon cavity types; the results show that a transmission efficiency exceeding $\sim60\%$ is obtained at the off resonant wavelengths.

4 Conclusion

We have compared three nanocavity designs, including a 1-D PhC nanobeam cavity, inline waveguide-integrated plasmon cavity, and a proposed square plasmon resonator embedded in the 1-D PhC nanobeam cavity (i.e., Combo cavity). Although the 1-D PhC nanobeam cavity exhibits a high $Q$-factor of $\sim10,000$ with a strong Purcell factor of $\sim626$ for the TM-polarized mode, it suffers a larger mode volume of up to $\sim9.7 (\lambda/2n)^3$ and relatively low optical field densities. The inline waveguide-integrated plasmon cavity shows a small mode volume of $\sim0.75 (\lambda/2n)^3$, but a low $Q$-factor of $\sim17.3$ due to both the efficient waveguide coupling and a larger metal loss from the plasmonic effect. The Combo cavity exhibits the smallest mode volume among the three cavities, allowing for a deep subwavelength mode volume of $\sim0.18 (\lambda/2n)^3$. This leads to the significantly enhanced interaction strength in the cavity, which is beneficial for active optoelectronic devices, such as lowering the drive power of electro-optic modulators or light sources. The combination of the plasmon cavity and the PhC represents potential building blocks for creating next-generation wavelength-scale light sources on chip.
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References


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