

Tunable wavelength-division multiplexing based on metallic nanoparticle arrays

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Received August 19, 2010; revised October 28, 2010; accepted November 8, 2010;
posted November 9, 2010 (Doc. ID 133664); published November 29, 2010

We report a tunable wavelength-division multiplexing (WDM) structure based on two-dimensional silver nanoparticle arrays. The linewidth of the multiple geometric resonances of the arrays is of the order of several nanometers generally, which guarantees high wavelength selectivity. Optical channels can be selectively activated by setting the polarization of the incident wave. The operation wavelength can be tuned from the visible to the near infrared, and the free spectral range can be adjusted from hundreds to tens of nanometers by varying the size of the constituent particles and the interparticle distances. The proposed structure can provide an extinction ratio of ~ 10 and a quality factor of ~ 700 . This tunable, easy-to-produce, and subwavelength WDM structure is desirable for plasmonic integrated circuits. © 2010 Optical Society of America

OCIS codes: 130.1750, 240.6680, 230.4555.

Wavelength-division multiplexing (WDM) is a crucial technique in telecommunications because it can increase the data transmission capacity of fiber-optic systems by dividing bandwidth based on wavelength. WDM systems have been proposed using many kinds of structures, such as arrayed waveguide gratings [1] and fiber Bragg gratings [2]. However, these devices typically have sizes of the order of centimeters or meters. Even though WDM devices based on photonic crystals a few tens of micrometers in size have been proposed [3,4], these devices are two-dimensional structures and still not sufficiently microscopic. Plasmonic structures can confine light energy on a subwavelength scale and are expected to realize the further miniaturization of many devices. A special design of a surface plasmon resonance (SPR) prism element is used to enable the WDM of serial sensing channels [5]. Metal-insulator-metal Fibonacci-sequence gratings can generate high-channel-count plasmonic stop bands [6]. A waveguide-ring-resonator-based add-drop multiplexer has been demonstrated experimentally [7]. However, these plasmonic structures are complex and demand high-precision fabrication technologies. Moreover, their tunabilities are very limited and they are difficult to integrate with other plasmonic devices.

The narrowest geometric resonances (<1 nm) have been achieved in one-dimensional silver nanoparticle arrays [8]. The resonance line shape is robust to random array disorder [9]. The Fano profiles of geometric resonances can be tuned effectively in binary arrays [10]. Metallic nanoparticle arrays possessing narrow geometric resonances are important for the realization of biosensors [11], surface-enhanced Raman scattering [12], and optical nanoantennae [13]. This structure can also be used in WDM.

In this Letter, we propose a tunable, compact, and easy-to-produce plasmonic structure that can achieve WDM based on silver nanoparticle arrays. The narrow width of the geometric resonances ensures high wavelength selectivity. Optical channels can be activated or deactivated by tuning the polarization of the incident

wave. The operation wavelength can be tuned from the visible to the near-IR, which covers all telecom bands. The free spectral range (FSR) can be adjusted from hundreds to tens of nanometers. The proposed WDM structure based on metallic nanoparticle arrays is a simple configuration and involves easy fabrication using electron beam lithography. In addition, it offers simple integration with other plasmonic devices.

A silver nanoparticle array used for WDM is shown schematically in Fig. 1(a). The interparticle distances are d_1 and d_2 along the x and y axes, respectively. The wave vector of the incident wave is perpendicular to the array plane, and the polarization vector is in the plane and has an azimuthal angle ϕ with respect to the x axis. A semianalytical coupled dipole method [14] is used, in which each particle is modeled by a dipole of polarizability α . Assuming an infinite array, the induced polarization of each particle can be expressed as $P = 1/(1/\alpha - S)$, where the dipole sum S embraces the contribution from all other dipoles. S can be evaluated numerically [14]:

$$S = \sum_{\text{dipoles}} \left[\frac{(1 - ikr_{ij}) \times (3\cos^2\theta_{ij} - 1)e^{ikr_{ij}}}{r_{ij}^3} + \frac{k^2 \sin^2\theta_{ij}e^{ikr_{ij}}}{r_{ij}} \right], \quad (1)$$

where r_{ij} is the distance from dipole i to dipole j and θ_{ij} is the angle between \mathbf{r}_{ij} and the polarization direction. Then the extinction cross section for each particle is obtained using the optical theorem [15], $C_{\text{ext}} = 4\pi k \text{Im}[1/(1/\alpha - S)]$.

The spectrum of a silver nanoparticle array is calculated, and the result is shown in Fig. 1(b). The dielectric permittivities of silver are from Lynch and Hunter [16], and the sphere polarizabilities are derived from the a_1 term of Mie theory [17]. Extinction cross sections are normalized by the geometrical area of the array. Here $d_1 = 800$ nm, $d_2 = 1000$ nm, $R = 100$ nm, and $\phi = \pi/4$. The spectrum of an isolated particle is included for comparison. As shown in Figs. 1(b) and 1(c), the extinction spectrum

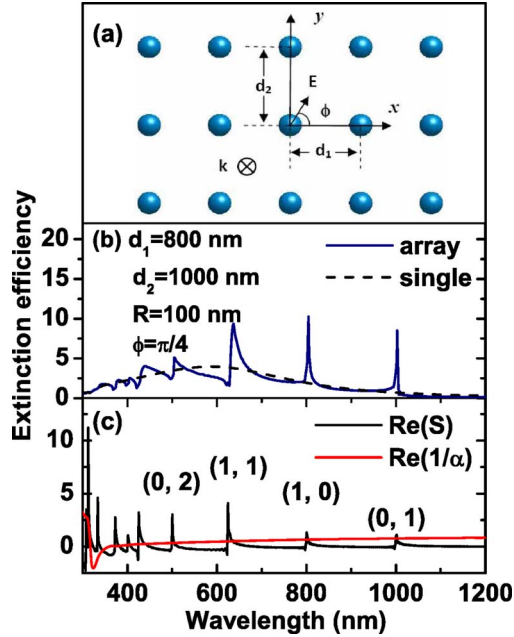


Fig. 1. (Color online) (a) Schematic of a two-dimensional silver nanoparticle array. (b) Extinction spectra of the array (solid curve) and a single particle (dashed curve). (c) Illustration of cancellation of the real parts of $\text{Re}(S)$ and $\text{Re}(1/\alpha)$.

exhibits resonance peaks near diffraction orders, which correspond to intersections of $\text{Re}(S)$ and $\text{Re}(1/\alpha)$. The three intense resonances at $\lambda = 637, 803$, and 1002 nm correspond to the $(1, 1)$, $(1, 0)$, and $(0, 1)$ diffraction orders, respectively. The multiple resonances mean that, for on-resonance wavelengths, the corresponding diffraction orders become evanescent, so that more energy is bounded near the array plane and less light can transmit through the array than for off-resonance wavelengths. Therefore, incident light with wavelengths in geometric resonance channels is transferred from the transmitted light to the evanescent energy and can be coupled to output waveguides, which allows the realization of WDM.

In Fig. 1(b), the FSRs of the three channels are 168 and 198 nm. In comparison with other WDM systems, the FSRs here are rather large, which makes the structure useful in coarse WDM. The FWHM of the $(1, 1)$, $(1, 0)$, and $(0, 1)$ channels is $\Delta\lambda = 33.0, 3.0$, and 1.5 nm and their quality factors (defined as $Q = \lambda/\Delta\lambda$) are 19, 268, and 668, respectively. Here, the extinction ratio (ratio of maximum to background) is 5–10. Thus, channels in the spectrum have high quality factors, which ensure good wavelength selectivity in the proposed WDM structure.

To study the tunability of the proposed WDM structure, we investigate the influence of the polarization of the incident wave and geometric parameters of nanoparticle arrays on the WDM properties.

First, we study the influence of the polarization of the incident wave. In Fig. 2(a), we show the extinction spectra of a set of arrays, in which ϕ varies from 0 to $\pi/2$. When $\phi = 0$, the $(1, 0)$ channel is totally deactivated. When distances between nanoparticles are large, the term proportional to $1/r$, which accounts for far-field interaction, dominates in Eq. (1). This term will vanish if $\theta_{ij} = 0$. When $\phi = 0$, the incident wave is polarized along the x axis, so that the far-field interaction among parti-

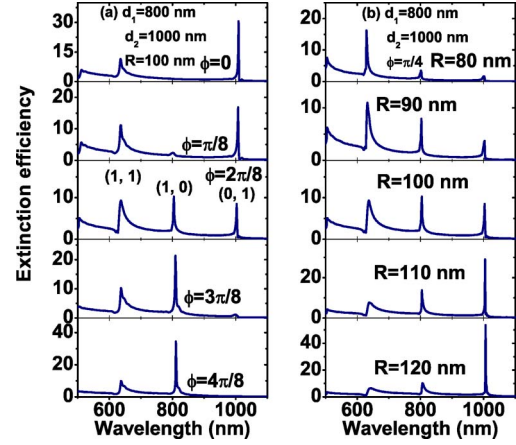


Fig. 2. (Color online) Extinction spectra of arrays. (a) ϕ varies from 0 to $\pi/2$. (b) R varies from 80 to 120 nm.

cles on the x axis and particles whose interparticle vectors are parallel to the x axis will be zero. As a result, the $(1, 0)$ channel disappears. As ϕ increases from $\pi/8$ to $3\pi/8$, the intensity of the $(1, 0)$ resonance increases, while the intensity of the $(0, 1)$ resonance decreases. When $\phi = \pi/2$, the $(0, 1)$ channel is totally deactivated. Ordinarily, wavelength-division demultiplexers are spectrographic devices that are not tunable, and their performance depends on the perfection of design and fabrication. In our proposed plasmonic WDM structure, the effective channels can be altered by changing the polarization of the incident wave.

The operation wavelength can be tuned from the visible to the near-IR. The localized surface plasmon resonance (LSPR) of an isolated particle redshifts when it increases in size. Intense geometric resonances are obtained only for wavelengths that fall within the envelope of the LSPR, which means that we can control the spectral range where intense resonances are produced. In Fig. 2(b), we show the spectra of arrays whose R varies from 80 to 120 nm. When $R = 80$ nm, only the $(1, 1)$ resonance shows remarkable intensity. With increasing R , both the $(1, 0)$ and $(0, 1)$ resonances increase in intensity until the three channels have the same intensity, which occurs near $R = 100$ nm. When R increases to 120 nm, there is only the $(0, 1)$ resonance left with remarkable intensity. If we increase the

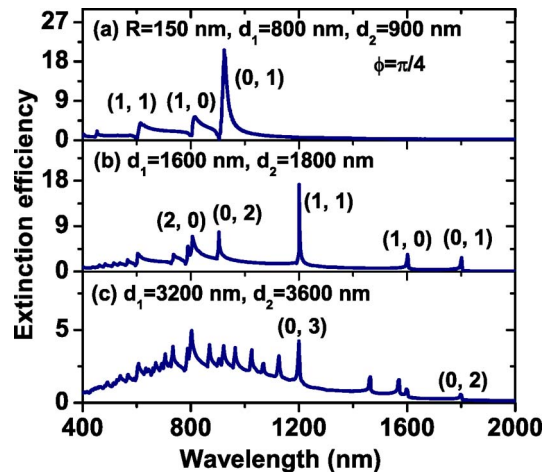


Fig. 3. (Color online) Extinction spectra of arrays in which interparticle distances are varied.

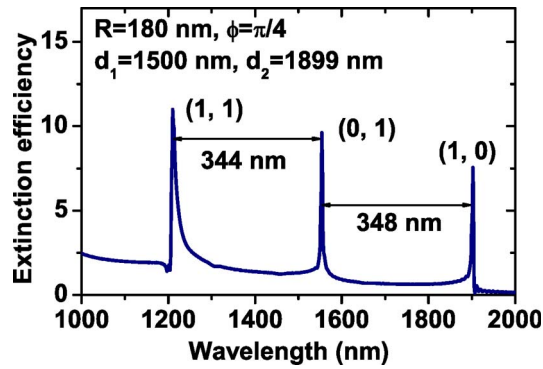


Fig. 4. (Color online) Extinction spectra of an array in which the middle channel is positioned near 1550 nm.

size of constituent particles accordingly, resonances can be obtained at even longer wavelengths. The operation wavelength of our WDM structure can be tuned over a wide range, which covers all telecom transmission windows.

The FSR can be adjusted from hundreds to tens of nanometers by varying interparticle distances. Geometric resonances corresponding to higher diffraction orders can be obtained within a particular spectral range by increasing interparticle distances. We show this characteristic in Fig. 3, where d_1 and d_2 are continuously increased. When $d_1 = 800$ nm and $d_2 = 900$ nm, there are three primary channels. When the interparticle distances are doubled, additional resonances appear near $\lambda = 1201$, 1602 , and 1802 nm. The FSR between the (0, 2) and (1, 1) channels is 297 nm. When the interparticle distances are quadrupled, from $\lambda = 800$ to 1200 nm, the FSRs are 66–74 nm. It is also shown in Fig. 3 that the tunability of the FSR and the number of channels are limited if a high extinction ratio is required.

To further exemplify the designability of the proposed WDM structure, we give an example in which three channels are roughly evenly spaced and the central channel is positioned at $\lambda = 1550$ nm. The (1, 1), (1, 0), and (0, 1) diffraction orders are used here. We set $d_1 = 1550$ nm, and then the other two diffraction orders are located at $d_1 - d_s$ and $d_1 + d_s$. Using relations among diffraction orders, we obtain $1/(1550 - d_s)^2 = 1/1550^2 + 1/(1550 + d_s)^2$. Solving this equation yields $d_s = 349$ nm. The extinction spectrum of the designed array is shown in Fig. 4. Here, peak wavelengths of the three channels are $\lambda = 1210$, 1554 , and 1902 nm. Thus, three approximately evenly spaced channels are obtained and the designability of the structure is demonstrated.

Finally, we briefly discuss the efficiency of the proposed WDM structure. For example, for the (0, 1) channel in Fig. 4, about 34% of the light power incident on the array plane has been lost at the peak wavelength. The

transmittance was 70%–85% at geometric resonance wavelengths in two-dimensional gold nanoparticle arrays [18], which is approximately in agreement with our results. Although the efficiency of the proposed WDM structure is not very high, the good tunability still makes it an attractive structure for many applications.

In summary, we have proposed and demonstrated theoretically a small-sized and easily integratable plasmonic structure to achieve WDM. The activation or deactivation of optical channels can be realized by changing the polarization of the incident wave. The operation wavelength can be tuned from the visible to the near-IR, and the FSRs can be adjusted from hundreds to tens of nanometers by varying the geometrical parameters of the structure. We believe this simple WDM structure will have important applications in plasmonic integrated circuits.

This work was supported by the National Natural Science Foundation of China (NSFC) under grants nos. 10874004, 10874010, and 10821062, and by the National Key Basic Research Program no. 2007CB307001.

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