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RESEARCH ARTICLE

Manipulation of spectral amplitude and phase with plasmonic nano-structures for information storage

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Abstract Optical storage devices, such as compact disk (CD) and digital versatile disc (DVD), provide us a platform for cheap and compact information storage media. Nowadays, information we obtain every day keeps increasing, and therefore how to increase the storage capacity becomes an important issue. In this paper, we reported a method for the increase of the capacity of optical storage devices using metallic nano-structures. Metallic nano-structures exhibit strong variations in their reflectance and/or transmittance spectra accompanied with dramatic optical phase modulation due to localized surface plasmon polariton resonances. Two samples were fabricated for the demonstration of storage capacity enhancement through amplitude modulation and phase modulation, respectively. This work is promising for high-density optical storage.

Keywords surface plasmon, data storage, localized surface plasmon resonance, Fano resonance

1 Introduction

Optical storage devices, such as compact disc (CD), digital versatile disc (DVD), and blue ray disc (BD), utilize the variation of reading laser power in reflectance/transmittance to retrieve information at a given wavelength [1–4]. In past decades, some other methods, such as holographic optical storage [5], near field optical storage [6–9], and three-dimensional (3D) optical storage by two-photon excitation [10,11], have been considered for high-density applications. In recent years, a concept of data storage through plasmonic resonances of metallic nano-structures has also been proposed [12,13]. Metallic nano-structures have the larger scattering cross section in comparison to that of dielectric materials, and exhibit strong variations in their reflectance and/or transmittance spectra due to localized plasmon polariton (LSP) excitation [14,15]. The LSP modes of a given nano-structure, determined by its material composition, geometry and dimensions, often exhibit unique amplitude as well as phase modulation in the optical reflectance/transmittance spectra. For example, Fig. 1 shows the phase and amplitude modulation as a function of wavelength for an array of 125-nm-long, 60-nm-width and 50-nm-thick gold nanorod on top of a 50-nm-thick MgF_2 on a gold mirror. At wavelength $\lambda \sim 1350$ nm, there is a plasmonic resonance mode with antipallel current oscillation that is accompanied with dramatic phase and amplitude modulation. Therefore, the amplitude or phase modulation at localized plasmon resonance can be used to provide the possibilities for information storage.

In this paper, we reported the results of information storage through the amplitude and phase modulation at localized plasmon polariton resonances, respectively. A sample was fabricated for the demonstration of information storage through amplitude modulation, and we studied the results involving 10 different nano-structural features covered by 135-nm-thick MgF_2 incorporated within a 500 nm × 500 nm area. In principle, the presence or absence of each such nano-feature gives rise to $2^{10} = 1024$ different reflectance/transmittance spectra when a short pulse (on the order of a few femtoseconds) or a super continuum laser is focused onto that 500 nm × 500 nm area. Assuming one could distinguish 2^{10} different spectra of a given spot during the available time, it should be possible to retrieve 10 binary digits (bits) from the area illuminated by a diffraction-limited focused beam. On the other hand, another sample consisting of gold nano-rods with varying sizes coupled to a gold mirror with 50-nm-thick MgF_2 as a spacer is applied for information storage

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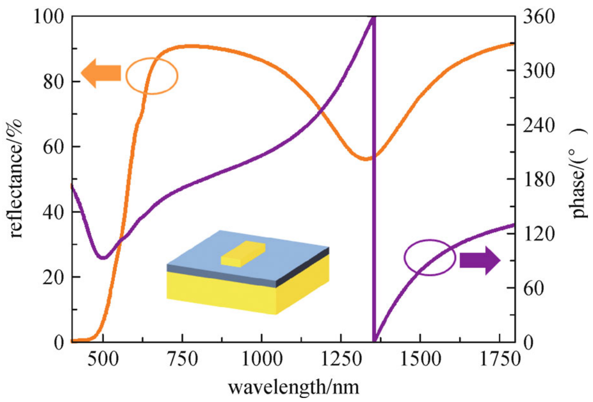

Fig. 1 Amplitude (orange curve) and phase (purple curve) modulation as function of wavelength for an array of 125-nm-long, 60-nm-width and 50-nm-thick gold nano-rods on top of a 50-nm-thick MgF_2 on a gold mirror. The period along both *x*- and *y*-direction is 250 nm. The plasmonic resonance shows dramatic phase and amplitude modulation at $\lambda \sim 1350$ nm

through phase modulation at plasmonic resonance. The 4-level discrete phase distribution of the letter "RCAS" is obtained by fast Fourier transforms method, and each phase corresponds to a specific length of nanorod. Similar to the reconstruction process of conventional hologram, the pre-designed image "RCAS" is then reconstructed with 780 nm laser illumination.

2 Experiments

Two samples were fabricated respectively on glass substrates with standard e-beam lithography and lift-off technique. We patterned the 200-nm-thick PMMA-495K e-beam resist using a commercial e-beam lithography system (Elionix ELS-7000) at the acceleration voltage of 100 keV with 30 pico-ampere of current. A thin Espacer layer was used to eliminate the static charge problem during e-beam exposure. After exposure, the samples were rinsed with de-ionized water to remove Espacer, then developed in solution of methyl isobutyl ketone (MIBK) and isopropyl alcohol (IPA) of MIBK:IPA = 1:3 for 1 min. Gold film of desired thickness was deposited subsequently by electron-beam evaporation. The samples were eventually soaked in acetone and shaken gently for over 12 h, and then the un-patterned regions were lifted off in an ultrasonic cleaner. Figures 2(a) and 2(b) show the schematic diagram and scanning electron microscope (SEM) images of the sample for information storage using amplitude modulation. In Fig. 2(b), the period along both *x*- and *y*-direction is 1 μm; each unit cell contains 10 different nano-patterns (see Fig. 2(a) for their feature sizes in nm unit). Figures 2(c) and 2(d) show the SEM images of the sample for information storage using phase modulation. For the demonstration of information storage through 4-level phase modulation, we selected four lengths L (L = 60, 103, 122 and 250 nm) of nano-rods with equal 60 nm line width, the nano-rods correspond to different phase modulations of 0°, 90°, 180° and 270° respectively.

For the spectral analysis, two spectrometers BRC642E and BTC261P (B&W Tek Inc.) were connected together through a bifurcated optical fiber for visible and near-infrared measurement, and integrated with an Olympus microscope IX70 (10 × objective, numerical aperture (NA) = 0.3, 100 W halogen light source and visible to near-infrared polarizer). The transmittance spectra were normalized by the transmissivity of an un-patterned region of the fused silica wafer. The spectra may show an interruption at wavelength $\lambda \sim 900$ nm resulted from the gap of Si and InGaAs detectors.

For the demonstration of information storage through phase modulation at LSP resonance, the phase distribution of the letter "RCAS" was calculated using computer generated hologram (CGH) method [16], then the continuous phase distribution was discrete into 4-level phase-only meta-hologram. The pixel size of meta-hologram was limited to 100 pixels × 100 pixels due to the time consumption of e-beam fabrication. The phase distribution as a function of the lengths of 50-nm-thick and 60-nm-width nano-rods was numerically calculated for wavelength $\lambda = 780$ nm. Four different lengths $L = 60$, 103, 122 and 250 nm were picked up that corresponds to the 4-level discrete phases. For the analysis of the reconstructed image of meta-hologram, a 780-nm laser, two linear polarizer (broadband polarizer, Edmund), a quarter waveplate, a focusing lens (with a 100.0 mm focal length) and meta-hologram sample were collinearly aligned, then the image was recorded by a sCMOS camera from PCO. Inc.

3 Results and discussion

In the case of information storage through amplitude modulation at localized surface plasmon resonances, Figs. 3(a) and 3(b) show the experimental transmittance spectra of the arrays illuminated at normal incidence using *x*- and *y*-polarized lights, respectively. In these figures, the spectrum depicted in black corresponds to the sample with all 10 nano-features present (i.e., the sample shown in Fig. 2(b)), whereas those depicted in color represent samples in which one of the nano-features (namely, ring, ellipse and square) has been removed. In Figs. 3(c) and 3 (d), the color spectra correspond to samples which contain, within each repeated unit cell, a single feature, e.g., a ring, an ellipse, or a square. The spectra differ from another under *x*- and *y*-polarized illuminations, since the localized surface plasmonic resonance is sensitive to the polarization state of incident light. For example, in the case of *x*-polarized illumination in Fig. 3(a), comparing the spectrum

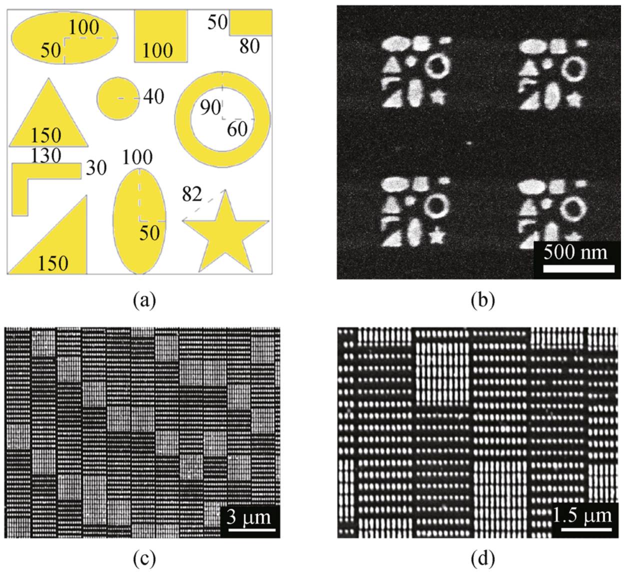

Fig. 2 Schematic diagram and SEM images of two samples for information storage through amplitude modulation (a), (b) or phase modulation (c), (d) at plasmonic resonances. (a) Diagram showing the dimensions (in nm) of each nano-feature embedded within a single 500 nm × 500 nm unit-cell; (b) SEM image taken on a small region from the fabricated sample before MgF_2 deposition. This array, which contains 10 different nano-patterns with a periodicity of 1.0 μm along both horizontal and vertical axes, was fabricated on glass substrate covered by a 135-nm-thick MgF_2 on its top; (c) SEM image of gold nano-rods with 60 nm line width and four different rod lengths L (L = 60, 103, 122 and 250 nm). The size of each pixel is 1.5 μm ×1.5 μm; (d) magnification image of frame (c)

in red with that in black, a peak at λ~1400 nm appears when the nano-ring is removed. Similarly, in the case of spectrum in yellow, by removing the ellipsed nano-structure, the peak at λ~600 nm becomes more distinct than that of the black spectrum. These variations of the red and the yellow spectra originate respectively from the plasmonic resonances of the nano-ring and the ellipse-shaped nano-feature. The peak in the red spectrum at λ~1400 nm in Fig. 3(a), for example, originates from removing the plasmonic resonance of the nano-ring seen in the red curve of Fig. 3(c). Similar spectral variations are observed while removing the other nano-features under y-polarized illumination in Figs. 3(b) and 3(d).

From the applicative point of view, the main issue of the information storage through spectral amplitude modulation is the full width at half maximum (FWHM) of plasmonic resonances that is determined by surface roughness, inherent metallic losses and the radiation losses of plasmonic resonances. The first one is due to metallization process during fabrication, it can be addressed by decreasing the metal deposition rate. The second one is due to the interband transition of electrons in metal and the electron scattering especially at grain boundary, the former can be solved by replacing Au with other materials that shows plasmon resonances in near-infrared region [17,18], the electron scattering can be dramatically decreased by physically or chemically growing single crystalline plasmonic layer [19,20]. In recent years, Fano resonance, resonance mode resulting from the near-field coupling between superradiant and subradiant plasmonic modes, have attracted wide attentions due to its high spectral quality factor [21,22]. Therefore, this feature of Fano resonance provides the possibility of enhancing the spectral variations for optical data storage through the coupling effect of nano-particles, and this feature is especially suited for high-density data storage applications. In the case of conventional optical storage, the signal obtained from recorded marks becomes less distinct when marks come closer together within a diffraction-limited spot. In the case of information storage through Fano resonance, however, readout signals become easier to detect when two nearby metallic nano-structures interact.

Another sample for information storage is consisted of 130-nm-thick gold mirror coupled with 50-nm-thick gold nano-rods and a 50-nm-thick MgF_2 as spacer. The phase of the reflected electromagnetic field is engineered by varying the length of rods along perpendicular direction. Therefore, the meta-hologram can generate the pre-designed patterns in far-field region by utilizing the nano-rods with varying geometry to satisfy the required phase distributions calculated by CGH. Figure 4(a) is the calculated reconstructed image “RCAS”, and Fig. 4(b) is its phase distribution obtained by CGH method. The phase distribution of the plasmonic hologram was quantized to 4 discrete phase levels 0°, 90°, 180° and 270°, and then decided by the specific length of the Au nanorod which correspond to length L = 60, 103, 122 and 250 nm, respectively. The total pixel numbers are 100 × 100. The pixel size is 1.5 μm × 1.5 μm. There are 10 × 5 Au nano-rods within a single pixel. Figure 4(c) shows the reconstructed image “RCAS” of hologram under polarized illumination along the long axis of nano-rods at λ = 780

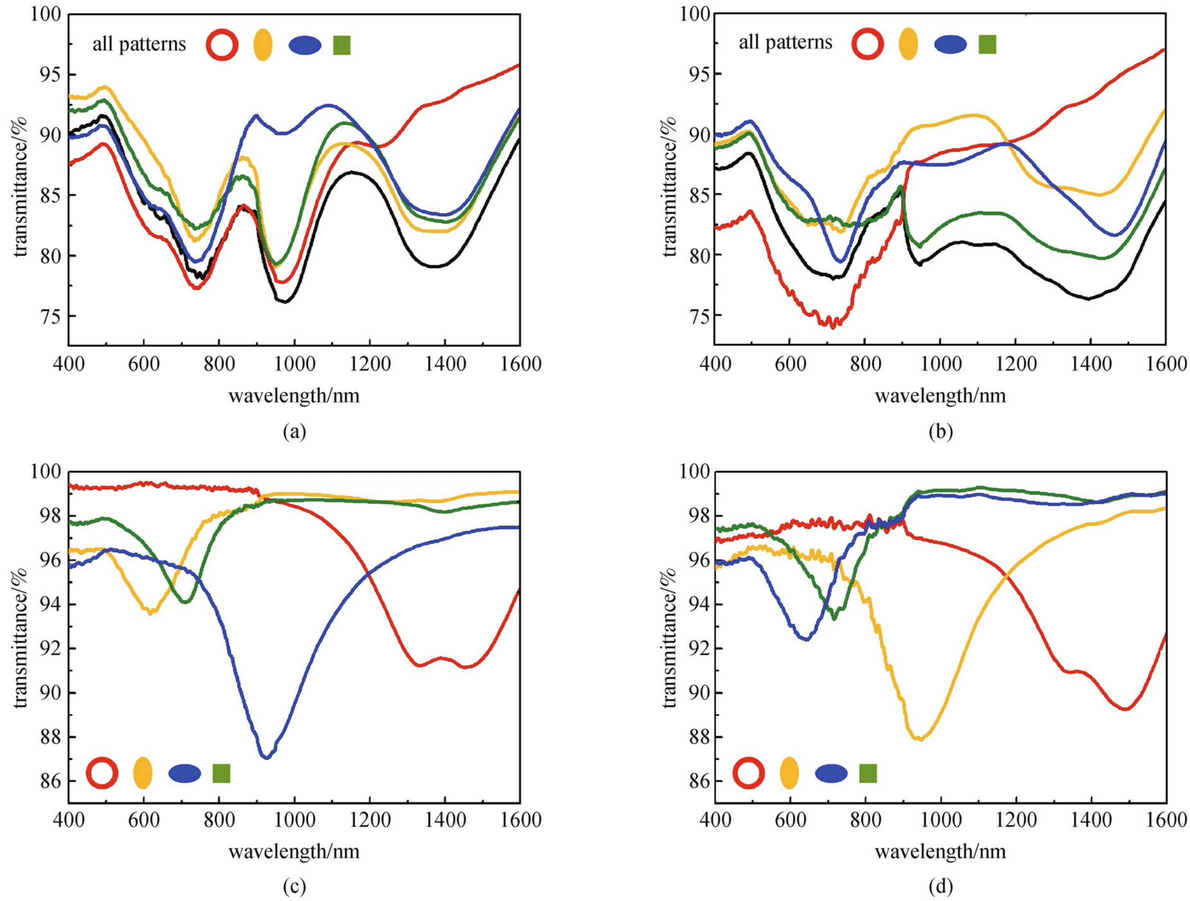

Fig. 3 Transmittance spectra of periodic arrays of identical unit cells for *x*-polarized and *y*-polarized illumination, each containing different nano-structures. In Figs. 3(a) and 3(b), the black spectrum corresponds to complete unit cells having all ten nano-features, whereas colored spectra represent unit cells with one feature removed; the missing feature is indicated in the legend. Figures 3(c) and 3(d) correspond to the unit cells contain a single nano-feature; the color (matched to the legend) identifies the nano-feature

nm. The efficiency, in comparison with the power of incident 780-nm laser, is defined as

$$Efficiency = \frac{P_{\text{RCAS}}}{P_{\text{laser}}} \times 100\%,$$

P_{RCAS} and P_{laser} are denoted as the optical power of "RCAS" pattern and the total power of incident beam, respectively. The measured efficiency of meta-hologram was ~21%, which is, to the best of our knowledge, the highest value in visible region among the holograms consisted of metallic metamaterials [23–25]. The high efficiency of our system was harvested from the reflected-only meta-surface composed of unit cells with high reflection amplitude (low loss), and can sufficiently modulate the reflection phase in a subwavelength with more levels since the simple design and fabrication process. The intensity variations in Fig. 4(c) is a result of the so-called "laser speckle effect" — a mutual interference of the scattered wave fronts of laser, which could be reduced if the pixel size could be scaled down to subwavelength scale.

4 Conclusions

In this paper, we studied the feasible concept of high-density optical data storage by employing plasmonic resonances, and demonstrated information storage through the modulation of amplitude and phase of light. The LSP-induced modulations of spectra in amplitude and phase corresponding to different shapes and orientations of metallic nano-particles can be employed as a promising candidate for storage capacity enhancement in optical storage media. The advantages of using plasmonic metallic nano-particles as storage media are that the pixel size of nano-structures can be as small as ~ $\lambda/5$, and therefore increase storage capacity in a given area with pronounced signal-to-noise ratio due to plasmon resonances. Moreover, the fabrication is compatible with today's semiconductor manufacture. It is also possible to further increase the storage capacity through plasmonic metallic nano-structures by taking good use of other dimensions, such as spatial dimension, wavelength, momentum and polarization of light [26–28].

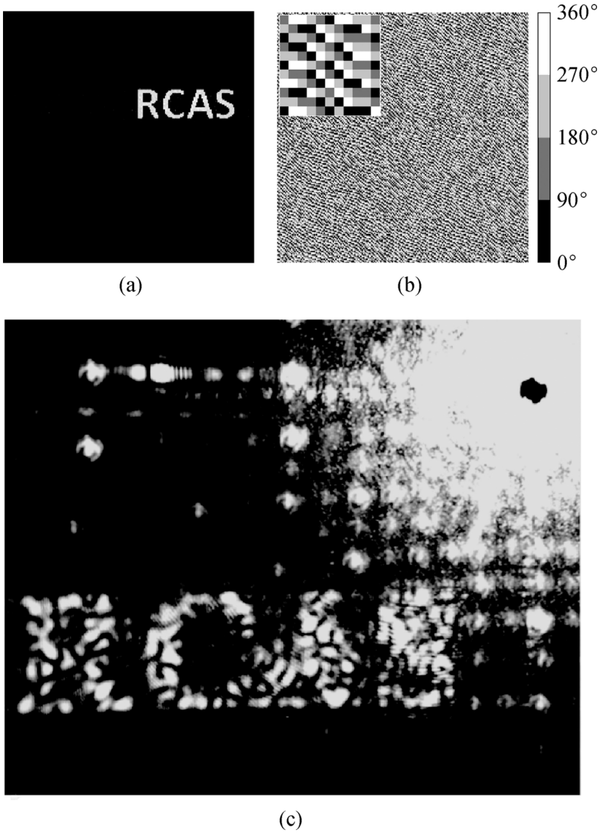

Fig. 4 Information storage through Au nano-rods. The phase information of letter "RCAS" is recorded by Au nano-rods on a gold mirror coupled to a 50-nm-thick dielectric buffer layer MgF_2. Figures 4(a) and 4(b) are the calculated reconstructed image "RCAS" and its four levels phase distribution. The experimental reconstructed image "RCAS" under 780-nm diode laser illumination is shown in Fig. 4(c)

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