Superposition behavior in Babinet s effect on the Au nano particles patterns

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ABSTRACT

The individual Babinet's effect of two types of complementary patterns can be added together on a composed pattern mixed with both patterns under the FTIR (Fourier Transform Infer-Red) spectroscopy measuring. Herein the added spectrum can show the superposition behavior in Babinet's effect. These two types of complementary patterns are Split Ring Resonator (SRR) and wire array (CLS Capacitively Loaded Strip) respectively. The mixed pattern is combined with SRR and wire array, which is so called the LHM (Left Handed Meta-material) pattern. Those samples are fabricated on Si wafer using standard integrated circuit (IC) processes. The metal conductors on the pattern surface are made of gold nano particles. Positive sample is deposited the Au nano particles on the periodic conducting parts of the pattern. Negative one is a reverse way that empties the conducting part and filled the surrounding space with Au particles.

Keywords Babinet's effect, left handed meta-material, nano Au particles, transmission enhancement

1 INTRODUCTION

Babinet's effect [1] is that the diffraction pattern of an aperture is the same as the pattern of an opaque object of the same shape illuminated in the same manner. The original principal stated by Babinet, which is in scalar form, and applied at large distances from the scattering screen where the energy densities of the electric and magnetic fields of the wave at any point are equal. In addition, the two spectra of complementary patterns are out of phase at each point on a detector. The electromagnetic Babinet principle for diffraction fields behind complementary perfectly conducting objects [2] relies on the duality of Maxwell's equations as well. Accordingly, the electromagnetic field at one position can be obtained by adding up those fields coming from different directions. Thus, the quantity of Babinet's effect on one mixed pattern can be added by each amount on those composed patterns. It is the goal of this study to demonstrate this superposition behavior by analyzing the FTIR spectra at LHM (Left Handed Meta-material) combined pattern. Especially, the superposition behavior of Babinet's effect is seldom reported since Babinet presented his observation. Interestingly, except Babinet effect, the optical characteristics of sub-wavelength transmission [3], doubly negative permeability and permittivity effects [4], and Wood's anomaly [5] were also observed in those spectra. The LHM is a specific pattern, which indicates the unique characteristics of a negative refraction index [4]. The pattern is a combination of the Split Ring Resonator (SRR) at $\mu < 0$ and the wire grating (CLS Capacitively Loaded Strip) pattern with $\varepsilon < 0$ [6].

Currently, novel properties of metal nano particles attract attention of researchers all over the world. For instance, Au nano particles are of specific behaviors and unique properties [7], and very useful in bios, optics and nano-electronics applications. Accordingly, we try to include Au nano particles into this LHM fabrication study and wish to investigate some new effects herein. Fortunately, the transmittance-enhanced behavior is found out obviously from the spectrum. The surface plasmon resonated effect [8] of Au nano particle on top pattern surface is supposed one of the attribution factors. Simultaneously, the combining effects at both the response of metamaterial pattern and the collective surface plasmon effect of the nano particles will be evaluated.

Some results of SRR and wire array investigation have been presented in other journals [9-11]. This work addresses only the superposition behavior in Babinet effect of LHM array obtained using FTIR. The description in this phenomenon will be presented following up the experiment. Section 2 states the experiment and characterization details. In Section 3, we report the main results and discuss the experimental data. Section 4 draws the conclusions.

2. Experiment

The patterned samples were fabricated using standard IC (integrated-circuit) processes. The substrate was a 6” double polished n-type silicon wafer. The wafer was cleaned by RCA cleaning. Reference [10] describes negative and positive patterning of samples. For positive one, the conducting parts in the pattern are filled with Au metal. Therefore, in the negative samples, the space along the conducting parts is filled with the gold particles. The conducting parts are thus empty and not covered by Au film; only SiO_2 remains on the Si substrate. Photographs were taken using SEM (Scanning Electronic Microscopy) instruments. Figure 1 shows the schematic graph of three types of patterns herein. The thickness of Au was ~ 20nm while the thickness of the Si substrate was ~0.7mm. The horizontal distance between the two LHM units was 3.2 μm and the vertical distance was 6.8 μm. Typically, the area of an entire LHM array sample is about 4 mm X 4 mm. An entire sample has *1 0×200*= 30,000 LHM units. The FTIR equipment used herein was QS 300 produced by Bio-Rad Laboratories, Inc. The range of wavenumbers of the light source was 4000~400 cm^{-1} (The wavelengths ranged from 2.5 to 25 μm). In this experiment the incident light was perpendicular to the pattern surface. Each of spectrums was obtained using 16scans.The time resolution was 2 sec and the scanning length was 30 sec.

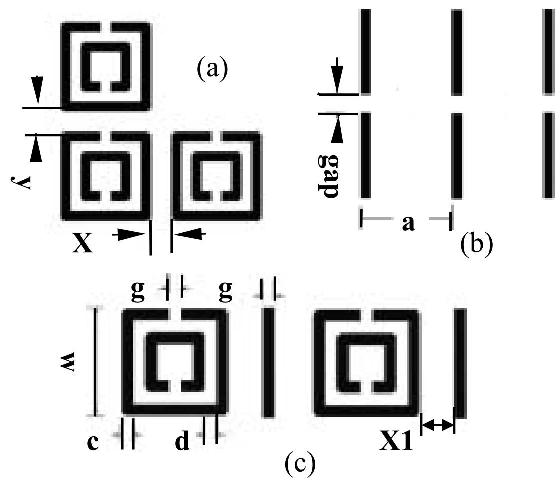


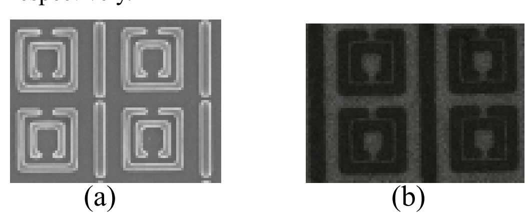
Fig.1 Schematic graphs of pattern (a) SRR (b) wire array. (c) LHM

c	d	g	w	X	Y	gap	X1	a
1	1.2	1.84	10.48	3.2	6.8	4.4	3.2	13.68

Table 1 Dimensions of all patterns. (unit：μm)

3. Results and Discussion

Figure 2 shows the SEM photograph of the positive and negative LHM arrays with 1000x and 35,000x magnifications, respectively.

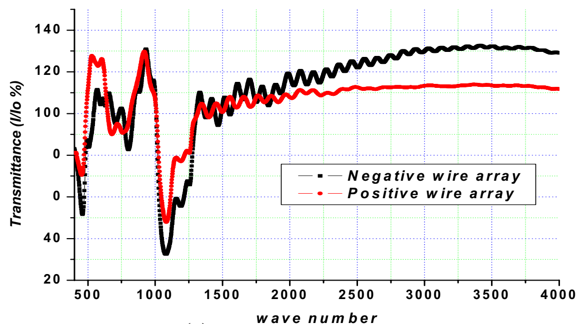


(a) (b)

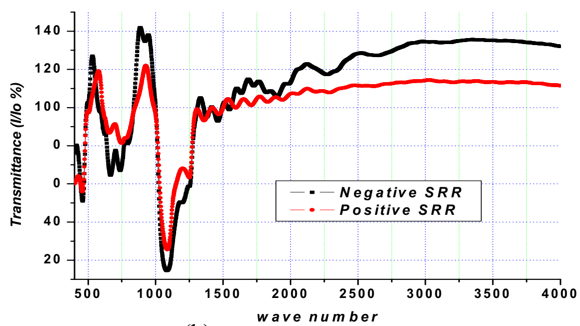
Fig. 2 SEM photographs of the complementary LHM patterns, (a) positive, (b) negative.

Figure 3 (a)-(c) display the FTIR transmittance spectra at 400~4000 cm^{-1}, corresponding to three types of patterns. From

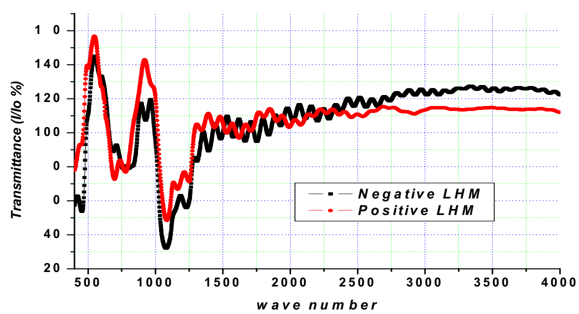
Fig. 3 (a), there are over 15 positions showing the Babinet's effect. Notably, whereon 5 points in this spectrum are below wave number 750 cm^{-1}. But no Babinet's effect can be observed at same region of wave number in spectrum of SRR pattern, shown as Fig. 3 (b). Additionally, only 4 points on the SRR spectrum exhibit Babinet effect, which all above wave number 750 cm^{-1}.



(a)



(b)



(c)

Fig. 3 The FTIR spectra of the Babinet's effect on the complementary SRR (a), wire array (b), and (c) LHM patterns.

However, there are more than 10 positions after wave number 750 cm^{-1} can show Babinet's behaviors in spectrum of wire array. Figure 3 (c) shows the spectrum of LHM, in which Babinet's behaviors are obvious in many regions. The range of wave numbers is from 696~710 cm^{-1} (14.1~14.4 μm), to 2926 cm^{-1} (3.4 μm). Babinet's behavior is clearly exhibited in over 25 positions, shown as Fig. 3 (c). Interestingly, only one position remained in this spectrum under wave number 750 cm^{-1} demonstrates the Babinet phenomenon. It illuminates the added result from superposing both spectra of two patterns during longer wavelength regime. Fig. 4 zooms into the SRR spectrum at 1200~2800 cm^{-1} to show clearer the relationship between the Babinet's behavior of complementary patterns. In this region, there are over 20 positions showing Babinet effect and some of them even occurring at same positions. For instance, at around 700, 1220, 1393, 1444, 1530, and 1800 cm^{-1}, the phase difference between waveforms is almost equal to π. Accordingly, it seems that the waveform of wire array spectrum dominates in shorter wavelength region and that of SRR does in longer range.

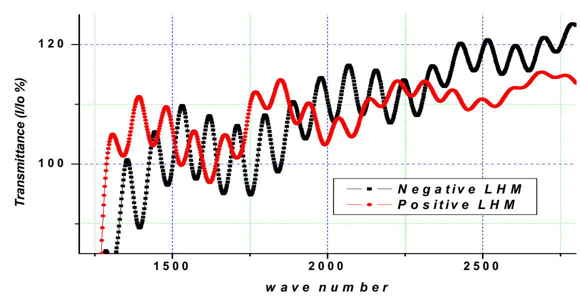


Fig. 4. Magnified spectrum of FTIR data that clearly shows the Basinet's effect in the 1200~2800 cm^{-1} regime.

Meanwhile, the transmittance (T) values can take to be $T_p(\lambda) = T_0(\lambda) \pm \Delta T(\lambda)$ and $T_n(\lambda) = T_0(\lambda) \pm \Delta T(\lambda)$ for that of positive and negative LHM patterns, respectively. $T_p(\lambda)$, and $T_n(\lambda)$ are the peak or valley transmittance values of the positive and negative patterns in the regions of Babinet's effects, and T_0 is the approximate transmission of the undiffracted light, which is considered to be the average value of T_p (λ)+ T_n (λ). Some T_0 values exceed 100%, probably because of the effect of transmission enhanced on both types of patterns. Where ΔT (λ), i.e., the difference between T_n and T_0, or T_p and T_0, is derived from the difference in diffraction from opaque obstacles in both LHM patterns. Notably, the complementary behaviors of the spectra are clearer than those of SRR and wire array pattern. It is seldom reported that Babinet's behavior is still exhibited under a sophisticated and periodic patterned array and even the superposition characteristics. Especially the incident wavelength is also compatible with the size of array. The annihilation effect of precise overlapping of two reciprocal patterns is thus observed. This finding is being investigated and will be discussed in a later study.

SEM observes that the dispersion of Au nano particles on the conducting surface in array pattern [10] is like the cluster in a semicontinuous metal. Accordingly, the Au nano particles could play a role of transmission enhancing, which is same as the percolation-enhanced nonlinear scattering (PENS) effect [12]. It is believed that would be a marked effect when polarized coherent light source is used.

4. Conclusion

Complementary LHM patterns were fabricated to include Au nano particles by standard IC processes. More than 25 Basinet's effects were observed over a wide range of wavelengths. Notably, those effects are coincident with the superposition of both spectra that correspond to SRR and wire pattern. Interestingly, some complementary waveforms arise even at the same positions. This result has seldom been reported and should be studied further. Whether the complementary spectra could be added together to yield a flat response was also investigated. The enhanced factor of the negative array exceeds that of the positive one, although the surface of the former is covered with more gold particles. Therefore the collective localized electric field, enhanced by Au nano particles, can combine with the surface plasmon to increase transmittance. Therefore further investigation is needed, particularly in the field distributed over the conductor in both types of LHM array.

Acknowledgement: The author would like to thank the National Science Council of the Republic of China, Taiwan for financially supporting this research under Contract No. NSC92-2215-E-492-009.

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