

Resonance hybridization in asymmetric split-ring resonator arrays - and detection of organic molecular Fano resonances

Nigel P. Johnson¹, Basudev Lahiri¹, Richard M. De La Rue¹, Ce Zhang² and Scott G. McMeekin³

¹University of Glasgow, School of Engineering, Rankine Building, Oakfield Avenue, Glasgow G12 8LT, UK; email: njohnson@elec.gla.ac.uk

²Department of Electronic Engineering, City University of Hong Kong, Kowloon, Hong Kong email: cezhang2@student.cityu.edu.hk

³School of Computing and Engineering, Glasgow Caledonian University, Glasgow, G4 0BA, UK email: Scott.McMeekin@gcu.ac.uk

Abstract

When two separate metallic arcs of different lengths share the same centre-of-curvature, they form asymmetric split ring resonators (A-SRRs). The resonances of the two arcs interact to produce steep slopes in the reflection spectrum, as well as a so-called trapped mode. We utilise a plasmon resonance hybridization model to understand the working of an array of A-SRR resonators (or nano-antennas) and show, by both experiment and simulation, that the A-SRR resonances are a 'modified linear superposition' of the individual plasmon resonances coming from each of the arcs. It is well known that the spectral position of the resonances can be tuned with size. We also show that, when PMMA is used as an organic probe on top of the A-SRR array, the phase and amplitude of a characteristic molecular Fano resonance associated with PMMA changes according to the spectral position of the trapped mode and the plasmonic reflection peaks. We further extend the study to show the quantitative effects of double A-SRRS and their resulting multiple trapped modes.

1. Introduction

Gold-based single-gap and asymmetric double-gap split-ring resonators (SRRs and A-SRRs) show strong resonances in both the microwave and infrared spectral regions [1-6] – and their applications include resonant optical detection of thin films of organic compounds.[4] We have studied the properties of arrays of A-SRRs that consist of two distinct metallic arcs, the left hand arc (LHA) and the right hand arc (RHA), that have different lengths but a common centre-of-curvature. Each arc has its own distinct plasmonic resonances. However their combination in an A-SRR arrangement leads to the individual responses being modified, producing locally sharper reflection peaks. Previous research has utilised the resonance hybridization model to analyze the response of different SRR formats.[7-8] In this contribution, we show that the concept of resonance hybridization applies to the interaction between the two distinct arcs of the A-SRRs that leads to characteristically sharp resonance peaks. Furthermore the presence of an absorptive reflection dip that has been identified as a 'trapped mode'[1] is an additional feature that results only from the collective behaviour of the two arc sections.

The potential use of the A-SRRs as a molecular probe has already been demonstrated using PMMA and other materials.[4] By varying the size of the structures, it is possible to change not only the amplitude but the phase of the molecular interaction with the A-SRR to produce Fano type resonance [4,7]. Later we show how the number of resonances can be increased (together with their selective sensing potential) by the use of Double A-SRRS - and we show the correlation of the resonances with those of the individual arc sections.

2. Experimental

A-SRRs with a radius of 600 nm and a strip width of 100 nm were fabricated on fused silica substrates - using a combination of electron-beam lithography (EBL) and lift-off. After patterning in PMMA resist, 2 nm of titanium and then 48 nm of gold were deposited, followed by lift-off. Square array patterns were written over areas of 300 μm x 300 μm . The reflection spectra of the fabricated structures were measured at normal incidence with polarised light in a Nicolet Continuum FTIR and IR microscope. The reflectance measurements were normalized with respect to the reflectivity of a gold mirror.

Simulations were carried out using both RSoft Fullwave and Lumerical software. The complex refractive index of the gold was modelled using a Lorentz-Drude model. Reflectance spectra (both experimental and simulation) of arrays of individual LHAs and RHAs, and that of an array of A-SRR's, are shown in Fig. 1, together with SEM images of the appropriate elements. The measurements and simulation are in reasonably good agreement. Discrepancies are attributable to imperfectly fabricated structures, and the fact that the experimental results are based on an array structure - whereas the modelling is performed on only one A-SRR structure, together with perfectly matched boundary conditions.

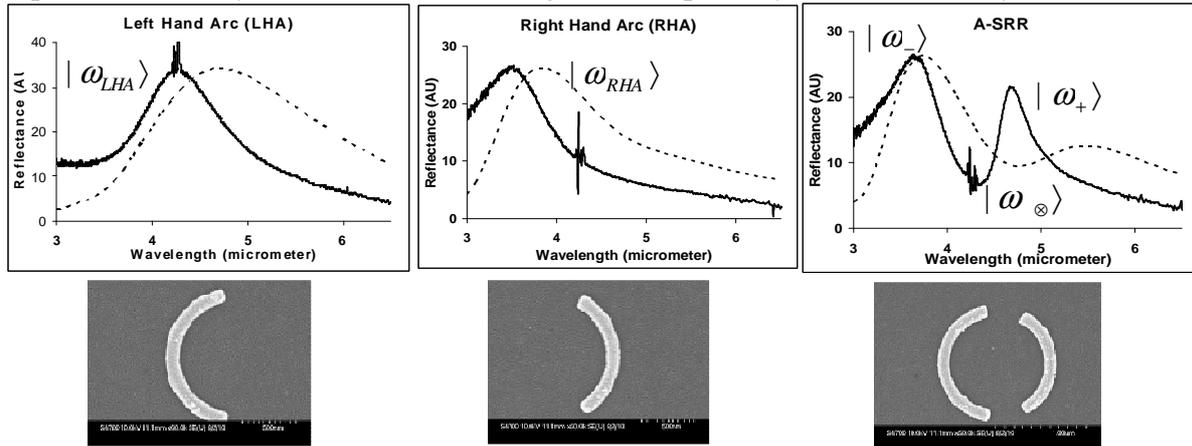


Fig. 1. SEM image and reflectance spectra of (a) LHA (b) RHA and (c) A-SRR. Solid curves denote experimental results and the dashed curves are for simulation. The resonances exhibited by single, individual arcs are distinct but are shifted when both arcs are positioned close to each other in the A-SRRs.

3. Discussion

The interaction between the fields of the left-hand and right-hand arcs results in red shifts in the resonance frequencies with respect to those of individual arcs. Shifts to lower frequencies are explained, in either case, by increases in the capacitive loading of the resonant arc due to the coupling between the two arcs. When the excitation frequency is shifted away from the resonance frequency of either arc, onto the excitation frequency of the trapped mode, the electric field distributions of the arcs oscillate in anti-phase with the adjacent arc. [9]

4. The effect of size on the amplitude and phase of the molecular Fano resonance.

PMMA can be used as a molecular probe due to the presence of carbonyl resonance at a wavelength of $5.7 \mu\text{m}$ [4].

As the size of the A-SRRs increases, both the amplitude and phase of the Fano resonance change as shown in Fig. 3. These results correspond respectively to the top of the reflectance peak, the trough or trapped mode - and the slope of the shorter wavelength peak. The largest *amplitude* effect appears at the trapped mode position, while the largest phase effect appears at a reflection peak.

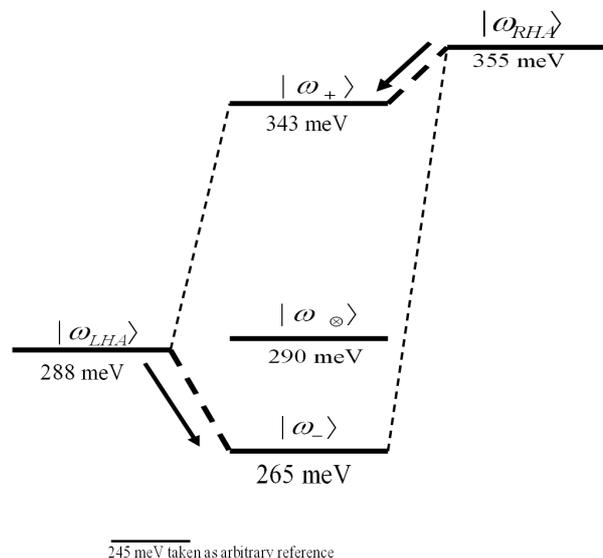


Fig.2 Resonance Hybridization diagram corresponding to the plasmonic eigenmodes obtained from the results of Fig.1.

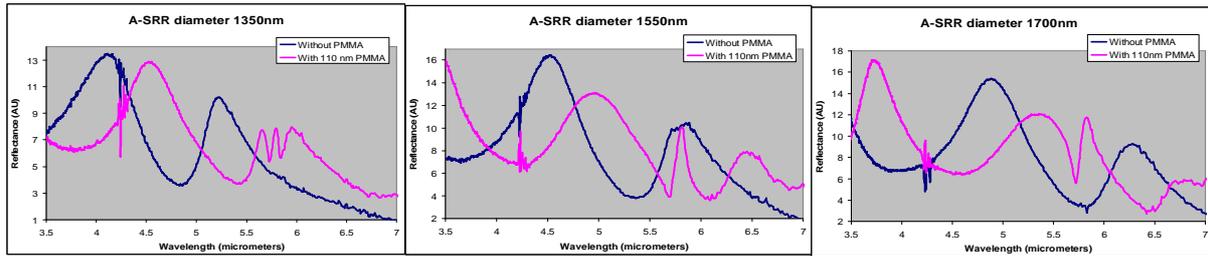


Fig. 3 The A-SRRS is increased from 1350 through 1550 to 1700 nm, the carbonyl bond resonance changes its phase relationship with respect to the background reflectivity of the ASRRs.

5. Extra trapped mode from use of Double A-SRRs

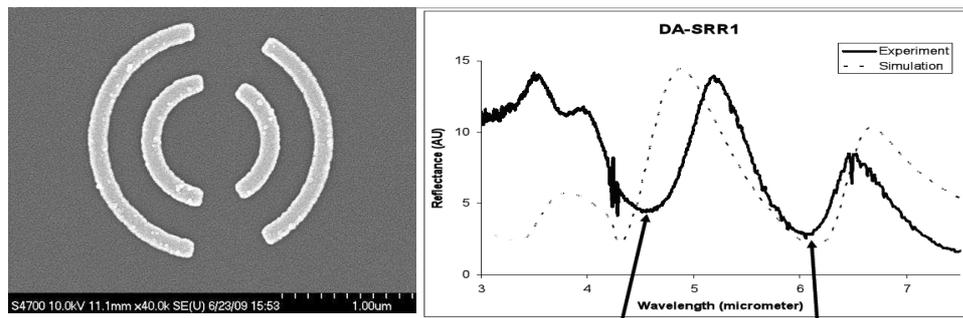


Fig.4 The Double A-SRRS with reflection spectra and simulations arrows show trapped modes.

The extension to multiple trapped modes (which has been confirmed elsewhere by reflectance and transmission spectra and thereby absorption) could be used to tune multiple molecular resonances.

6. Conclusions

The spectral position of A-SRRs and double A-SRR resonances are understandable in terms of resonance hybridisation. The interaction of molecular resonances with the A-SRRs can be described as a Fano resonance. Extra trapped modes can be generated with double A-SRRs.

7. Acknowledgements

We acknowledge support from EU project ECONAM, COST action MP0702 and the staff and facilities in the James Watt Nanofabrication Centre, Glasgow.

References

- [1] V. A. Fedotov, M. Rose, S. L. Prosvirnin, N. Papasimakis and N. I. Zheludev, Phys. Rev. Lett. 99, 147401 (2007).
- [2] C. Debus and P. H. Bolivar, Appl. Phys. Lett. 91, 184102, (2007).
- [3] C. Debus and P. H. Bolivar, Proc. SPIE. 6987,3 (2008).
- [4] B. Lahiri, A. Z. Khokhar, R. M. De La Rue, S. G. McMeekin, and N. P. Johnson, Opt. Express 17, 1107, 2009.
- [5] B. Lahiri, S. G. McMeekin, A. Z. Khokhar R. M. De La Rue, and N.P. Johnson, Opt. Express 18, 3210, 2010.
- [6] B. Lahiri, R. Dylewicz, R. M. De La Rue, and N.P. Johnson, Opt. Express 18, 11202, 2010.
- [7] H. Guo, N. Liu, L. Fu, T. P. Meyrath, T. Zentgraf, H. Schweizer and H. Giessen, Opt. Express. 15, 12095 2007.
- [8] For a review of Fano resonances see Boris Luk'yanchuk, et al, Nature Materials 9, 707–715 (2010)
- [9] Submitted to APL