

# Magneto-Elastic Tuning of Narrow-Band Resonant Transmission via Intrinsic Rotation in Metamaterials

Tatsunosuke Matsui<sup>1,\*</sup>, Mingkai Liu<sup>2</sup>, David A. Powell<sup>2</sup>, Ilya V. Shadrivov<sup>2</sup>, and Yuri S. Kivshar<sup>2</sup>

<sup>1</sup>Department of Electrical and Electronic Engineering and The Center of Ultimate Technology on Nano-Electronics, Mie University, Mie, Japan

<sup>2</sup>Nonlinear Physics Centre and Centre for Ultrahigh-bandwidth Devices for Optical Systems (CUDOS), Australian National University, Canberra, Australia

\*corresponding author, E-mail: matsui@elec.mie-u.ac.jp

## Abstract

We demonstrate magneto-elastic tuning of narrow-band resonant transmission analogous to the electromagnetically-induced transparency (EIT) in tri-resonator system consisted of two split-ring resonators (SRRs) and one closed-ring resonator (CRR). To tune the resonant transmission, intrinsic rotation of one of the SRRs due to the near-field interaction between SRRs was utilized. Our findings may open the way to access to the time-domain response of the system by optical means via magneto-elastic metamaterials.

## 1. Introduction

Since Pendry *et al.*, put forward the basic concept of metamaterials [1], numerous studies have been carried out from various viewpoints [2]. In metamaterials, artificially designed subwavelength resonant structures (meta-atoms) such as split-ring resonator (SRR) play crucial roles in obtaining rich variety of unique responses to electromagnetic fields.

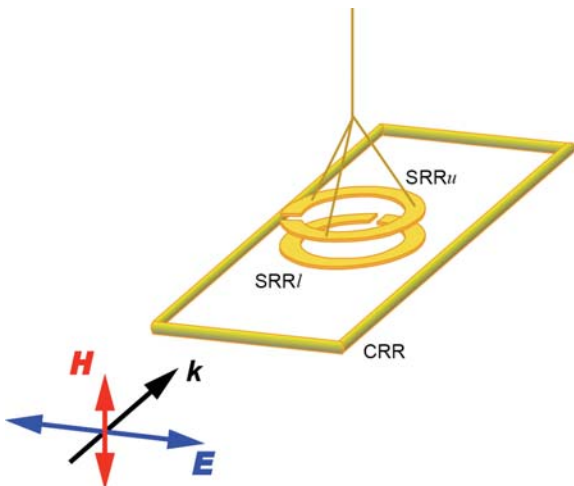


Figure 1: Schematic representation of tri-resonator device. The CRR and the lower SRR (SRRl) are fixed on the dielectric substrate. The upper SRR (SRRu) is suspended with a thin rubber wire and free to rotate about the common axis

Recent progress of metamaterials research enables us to access the mechanical deformation or movement of the system [3,4] via near-field interaction between meta-atoms [5]. Here we demonstrate that the narrow-band resonant transmission analogous to the electromagnetically-induced transparency (EIT) [6-8] in tri-resonator system consisted of two SRRs and one closed-ring resonator (CRR) can be electromagnetically tuned utilizing the intrinsic rotation of one of the SRRs due to the near-field interaction between SRRs in the magneto-elastic metamaterials. Our findings may be used for the fabrication of tunable slow light device utilizing the magneto-elastic metamaterials.

## 2. Experiment

In this section, experimental procedures of the device fabrication and microwave pump-probe measurements are briefly summarized. Detailed information can be found in ref [4].

### 2.1. Magneto-elastic tri-resonator device

A schematic of the tri-resonator device is given in Fig. 1 (the dielectric substrates are omitted). We have used two Cu SRRs printed on Rogers R4003 substrates. The inner radius, track width, slit width and the thickness of each SRR are 3.2 mm, 1 mm, 0.2 mm and 0.035  $\mu\text{m}$ , respectively. The real dielectric constant ( $\epsilon_r$ ) and loss tangent of the dielectric are 3.5 and 0.0027, and the thickness of the dielectric substrate is 0.5 mm. The lower SRR (SRRl) is fixed, but the upper SRR (SRRu) is suspended with a thin rubber wire and free to rotate about the common axis responding to the pump microwave signal. Another closed-ring resonator (CRR) with rectangle profile made of Cu wire is placed such that the two SRRs and the CRR are aligned coaxially. The length and the width of the rectangle of the CRR are carefully designed to obtain EIT-like narrow-band transmission. The horizontal position and the initial twist angle of the SRRu are also carefully adjusted. The tri-resonator device is placed such that the common axis of the device is well aligned along the center axis of a rectangular waveguide for the microwave transmission measurement.

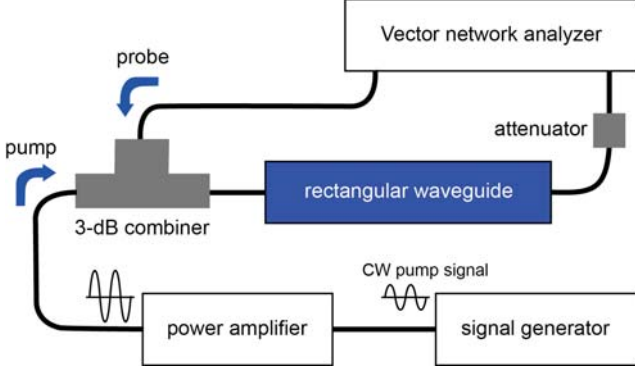


Figure 2: Schematics of the microwave pump-probe measurement setup.

## 2.2. Microwave pump-probe measurement

A schematic of the experimental setup for the microwave pump-probe measurement is shown in Fig. 2. The device is placed in the center of a WR229 rectangular waveguide, in which only the fundamental ( $TE_0$ ) mode can be supported in the frequency range of our interest below around 4 GHz.

The CW pump signal from a signal generator (HP 8673B) is amplified by a power amplifier (HP 83020A) and sent into the waveguide. The transmission spectra are measured using a vector network analyzer (Rohde and Schwarz ZVB-20). Each time the pump signal is sent to the waveguide, the system was left untouched until the system reaches steady state before recording the transmission data.

## 3. Results and Discussion

In Fig. 3, measured transmission coefficients of the tri-resonator device placed in the waveguide pumped with a CW signal with 3.70 GHz are summarized. In well adjusted tri-resonator system of two SRRs and one CRR, EIT-like narrow transmission band appeared in the middle of transmission dip with relatively wider bandwidth. We have confirmed using numerical simulation that this narrow-band transmission is attributed to the interference between the dipole-like resonant mode along the long edges of the CRR, which cannot be excited in normal condition, and the hybrid mode of two SRRs and dipole-like resonant mode along the short edges of the CRR (data is not shown). Mode hybridization between three resonators makes it possible to access the “dark” mode along the long edges of the CRR, and thus give an EIT-like narrow-band transmission. The SRRu is initially placed such that the mode matching is slightly off and gives weak (wider) EIT-like response without pumping. Upon increasing the pumping power, the EIT-like transmission band becomes much narrower. This spectral narrowing should be attributed to the better mode matching between wide-band transmission dip and the narrow-band “dark” mode induced by the intrinsic rotation of the freely rotatable SRRu [4] enabled by the near-field interaction between SRRs. On the contrary, the frequency of the EIT-like transmission peak does not shift much under

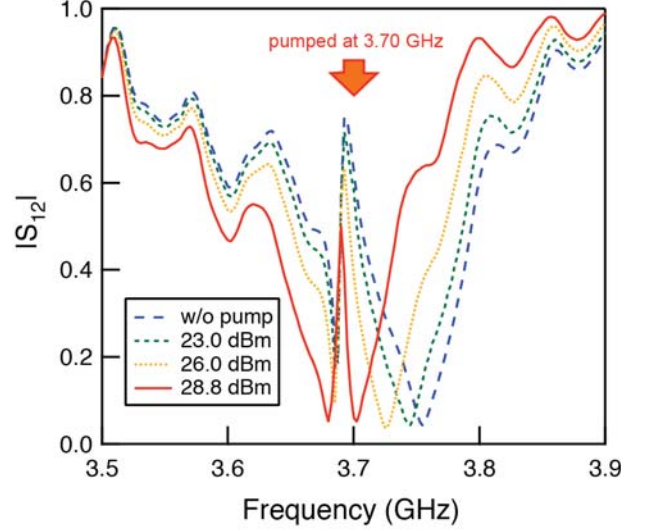


Figure 3: Measured transmission coefficients of the tri-resonator device placed in the waveguide. The system is pumped with CW signal with 3.70 GHz.

different pumping power. It is well known that the EIT-like narrow-band transmission gives larger dispersion in the group index and significantly slows down the speed of light [6-8]. Our results imply that the magneto-elastic metamaterials may be applied to the tunable slow light applications.

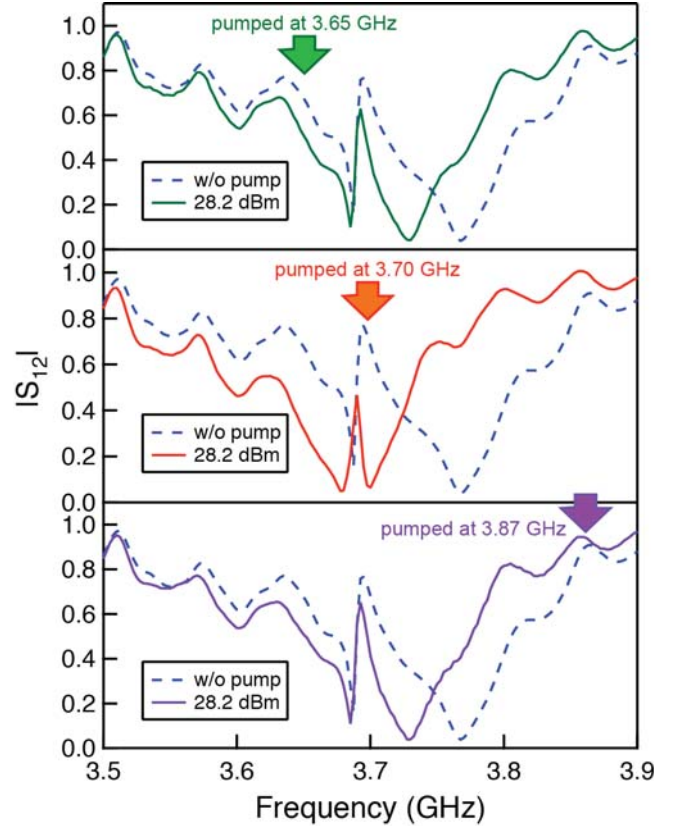


Figure 4: Measured transmission coefficients of the tri-resonator device placed in the waveguide. The system is pumped with CW signal with different frequencies of 3.65, 3.70, 3.87 GHz from top to bottom.

In Fig. 4, measured transmission coefficients of the tri-resonator device placed in the waveguide pumped with a CW signal of different frequencies of 3.65, 3.70 and 3.87 GHz are summarized. As can be seen, the system can be driven with CW microwave pump signal ranging from 3.65 up to 3.87 GHz. Pumping at around EIT-like transmission peak frequency around 3.70 GHz gives the best narrowing of the EIT-like transmission peak.

#### 4. Conclusions

We have experimentally investigated transmission characteristics of tri-resonator system consisted of two SRRs and one CRR under different CW pumping conditions using microwave pump-probe experiment. One of the SRRs is made free to rotate about the common axis of the device responding to the pumping electromagnetic signal. We have obtained EIT-like narrow-band resonant transmission in the carefully optimized device and realized significant spectral narrowing utilizing the intrinsic rotation of freely rotatable SRR induced by the near-field interaction between SRRs. Our findings may open the way for the application of magneto-elastic metamaterials to the tunable slow light devices.

#### Acknowledgements

This work was financially supported by Australian Research Council. T.M. acknowledges funding from the TEPCO Memorial Foundation.

#### References

- [1] J. B. Pendry, A. J. Holden, D. J. Robbins, W. J. Stewart, Magnetism from Conductors, and Enhanced Non-Linear Phenomena, *IEEE Trans. Microwave Theor. Tech.* 47, pp.2075-2084, 1999.
- [2] N. I. Zheludev, Y. S. Kivshar, From metamaterials to metadevices, *Nature Materials* 11, pp.917-924, 2012.
- [3] M. Lapine, I. V. Shadrivov, D. A. Powell, Y. S. Kivshar, Magnetoelastic metamaterials, *Nature Materials* 11, pp.30-33, 2012.
- [4] M. Liu, Y. Sun, D. A. Powell, I. V. Shadrivov, M. Lapine, R. C. McPhedran, Y. S. Kivshar, Nonlinear response via intrinsic rotation in metamaterials, *Phys. Rev. B* 87, pp.235126-1-6, 2013.
- [5] D. A. Powell, K. Hannam, I. V. Shadrivov, Y. S. Kivshar, Near-field interaction of twisted split-ring resonators, *Phys. Rev. B* 83, pp.235420-1-6, 2011.
- [6] L. V. Hau, S. E. Harris, Z. Dutton, C. H. Behroozi, Light speed reduction to 17 metres per second in an ultracold atomic gas, *Nature* 397, pp.594-598, 1999.
- [7] Q. Xu, S. Sandhu, M. L. Povinelli, J. Shakya, S. Fan, M. Lipson, Experimental Realization of an On-Chip All-Optical Analogue to Electromagnetically Induced Transparency, *Phys. Rev. Lett.* 96, pp. 123901-1-4, 2006.
- [8] S. F. Mingaleev, A. E. Miroshnichenko, Y. S. Kivshar, Coupled-resonator-induced reflection in photonic-crystal waveguide structures, *Opt. Express* 16, pp. 11647- 11659, 2008.