Tunable Transparency Window with Meta-Molecules Utilizing Superconducting Dark Resonators

Cihan Kurter[1], Philippe Tassin[2,3], Lei Zhang[2], Thomas Koschny[2], Costas M. Soukoulis[2,4], Alexander P. Zhuravel[5], Alexey Ustinov[6], Steven M. Anlage[1,6]

[1] Physics Department, Center for Nanophysics and Advanced Materials, University of Maryland, College Park, MD 20742-4111 USA
Fax: +1 301-405-3779; email: anlage@umd.edu
[2] Ames Laboratory—U.S. DOE and Department of Physics and Astronomy, Iowa State University, Ames, IA 50011, USA
e-mail: tassin@ameslab.gov
[3] Department of Applied Physics and Photonics, Vrije Universiteit Brussel, Pleinlaan 2, B-1050 Brussel, Belgium
[4] Department of Material Science and Technology, and Institute of Electronic Structure and Lasers (IESL), FORTH, University of Crete, 71110 Heraklion, Crete, Greece
e-mail: soukoulis@ameslab.gov
[5] B. Verkin Institute for Low Temperature Physics & Engineering, National Academy of Sciences of Ukraine, 61164 Kharkov, Ukraine
Fax: :+38 057 3403370; email: zhuravel@ilt.kharkov.ua
[6] Physikalisches Institut and DFG-Center for Functional Nanostructures (CFN), Karlsruhe Institute of Technology, D-76131 Karlsruhe, Germany
Fax: +49 721-608-6103; e-mail: alexey.ustinov@pi.uni-karlsruhe.de

Abstract

We have developed a high quality factor microwave-frequency meta-molecule to demonstrate a classical optical phenomenon analogous to electromagnetically induced transparency (EIT). The two-dimensional design employs two planar Nb split rings acting as dark resonators symmetrically placed around a thick Au strip acting as a bright resonator. When Nb is in the superconducting state, the significant loss gradient between Nb and Au opens a transparency window along with a strongly enhanced group delay. The data show a systematic evolution with increasing temperature in the superconducting state of Nb, and the features disappear in the resistive state when the loss gradient between the two types of resonators closes. We have also observed switching of the transparency window at high incident microwave power. The experimental results are in good agreement with numerical simulations of the same structure. Laser scanning microscopy images of the microwave current distributions in the dark resonators are also in good agreement with simulations.

1. Introduction

Metamaterials are engineered materials composed of small electrical circuits producing novel interactions with electromagnetic waves. Recently, a new class of metamaterials has been created to mimic the behaviour of media displaying electromagnetically induced transparency (EIT) [1]. These metamaterials employ combinations of carefully designed sub-wavelength resonators having vanishing (dark elements) and non-vanishing (radiative elements) dipole interaction with the incident electromagnetic waves [2]. Here we introduce a planar EIT metamaterial that creates a very large loss contrast between the dark and radiative resonators by employing a superconducting Nb film in the dark element and a normal metal Au film in the radiative element [3]. Below the critical temperature of Nb, the resistance contrast established opens up a transparency window along with a large enhancement in group delay, enabling a significant slowdown of electromagnetic waves. We further show that superconductivity allows for precise control of EIT response through changes in the superfluid density [4, 5]. The resonant EIT features can be sensitively tuned as temperature varies until the breakdown of the superconducting state at T_c causes the transparency window to be switched off. Such tunable or switchable metamaterials may be useful for telecommunication purposes because of their large phase shifts and delay-bandwidth products.

Acknowledgements

The work at Maryland was supported by the Office of Naval Research Award No. N000140811058 and 20101144225000, the U.S. Department of Energy (High Energy Physics) under Contract No. DESC0004950, the Office of Naval Research/UMD AppEl Center, task D10 (Award No. N000140911190), and CNAM. The work at Ames Laboratory was partially supported by the U.S. Department of Energy, Office of Basic Energy Science, Division of Materials Sciences and Engineering (Ames Laboratory is operated for the U.S. Department of Energy by Iowa State University under Contract No. DE-AC02-07CH11358) (computational studies), the U.S. Office of Naval Research Award No. N000141010925 (synthesis and characterization of samples), and the European Community FET project PHOME, Contract No. 213310 (theoretical studies). The work in Karlsruhe is supported by the Fundamental Researches State Fund of Ukraine and the German International Bureau of the Federal Ministry of Education and Research (BMBF) under Grant Project No. UKR08/011, and a NASU program on “nanostructures, materials and technologies.” P.T. acknowledges a fellowship from the Belgian American Educational Foundation.

References

[1] N. Papasimakis, V. A. Fedotov, N. I. Zheludev, S. L. Prosvirnin, Metamaterial analog of electromagnetically induced transparency. *Phys. Rev. Lett*. vol. 101, 253903, 2008.

[2] L. Zhang, Philippe Tassin, Thomas Koschny, Cihan Kurter, Steven M. Anlage, and C. M. Soukoulis, Large group delay in a microwave metamaterial analogue of electromagnetically induced transparency. Appl. Phys. Lett. vol. 97, 241904, 2010.

[3] Cihan Kurter, Philippe Tassin, Lei Zhang, Thomas Koschny, Alexander P. Zhuravel, Alexey V. Ustinov, Steven M. Anlage, and Costas M. Soukoulis, Classical Analogue of Electromagnetically Induced Transparency with a Metal/Superconductor Hybrid Metamaterial, Phys. Rev. Lett. (in press). arXiv:1103.5503.

[4] S. M. Anlage, The Physics and Applications of Superconducting Metamaterials, *J. Opt.* vol. 13, 024001, 2011.

[5] C. Kurter, A. P. Zhuravel, J. Abrahams, C. L. Bennett, A. V. Ustinov, S. M. Anlage, Superconducting RF Metamaterials Made with Magnetically Active Planar Spirals, *IEEE Trans. Appl. Supercond*. Vol. 29, 709-712, 2011.