Nonlinear magnetic metamaterials

Ilya V. Shadrivov[1], **Alexander B. Kozyrev**[2], **Daniel W. van der Weide**[2], **and Yuri S. Kivshar**[1]

[1] *Nonlinear Physics Center, Research School of Physical Sciences and Engineering, Australian National University, Canberra ACT 0200, Australia*

[2] *Department of Electrical and Computer Engineering, University of Wisconsin-Madison, Madison WI 53706, USA*

Abstract: We study experimentally nonlinear tunable magnetic metamaterials operating at microwave frequencies. We fabricate the nonlinear metamaterial composed of double split-ring resonators where a varactor diode is introduced into each resonator so that the magnetic resonance can be tuned dynamically by varying the input power. We demonstrate that at higher powers the transmission of the metamaterial becomes power-dependent and, as a result, such metamaterial can demonstrate various nonlinear properties. In particular, we study experimentally the power-dependent shift of the transmission band and demonstrate nonlinearity-induced enhancement (or suppression) of wave transmission.

OCIS codes: (160.3918) Materials : Metamaterials; (350.4010) Other areas of optics : Microwaves

References and links

1. C. M. Soukoulis, “Bending back light: The science of negative index materials,” Opt. Photon. News **17,** 16–21 (2006).
2. D. R. Smith, W. J. Padilla, D. C. Vier, S. C. Nemat Nasser, and S. Schultz, “Composite medium with simultaneously negative permeability and permittivity,” Phys. Rev. Lett. **84,** 4184–4187 (2000).
3. A. A. Zharov, I. V. Shadrivov, and Yu. S. Kivshar, “Nonlinear properties of left-handed metamaterials,” Phys. Rev. Lett. **91,** 037401–4 (2003).
4. M. Gorkunov and M. Lapine, “Tuning of a nonlinear metamaterial band gap by an external magnetic field,” Phys. Rev. B **70,** 235109–9 (2004).
5. M. Lapine, M. Gorkunov, and K. H. Ringhofer, “Nonlinearity of a metamaterial arising from diode insertions into resonant conductive elements,” Phys. Rev. E **67,** 065601–4 (2003).
6. S. Lim, C. Caloz, and T. Itoh, “Metamaterial-based electronically controlled transmission-line structure as a novel leaky-wave antenna with tunable radiation angle and beamwidth,” IEEE Trans. Microwave Theory Tech. **52,** 2678–2690 (2004).
7. H. T. Chen, W. J. Padilla, J. M. O. Zide, A. C. Gossard, A. J. Taylor, and R. D. Averitt, “Active terahertz metamaterial devices,” Nature (London) **444,** 597–600 (2006).
8. I. V. Shadrivov and Yu. S. Kivshar, “Nonlinear Effects in Left-Handed Metamaterials,” in *Physics of Negative refraction and Negative Index Materials*, Vol. 98 of *Springer Series in Materials Science*, C. M. Krowne and Y. Zhang, eds., (Springer-Verlag, Berlin, 2007), pp. 331–371.
9. I. V. Shadrivov, S. K. Morrison, and Yu. S. Kivshar, “Tunable split-ring resonators for nonlinear negative-index metamaterials,” Opt. Express **14,** 9344–9349 (2006).
10. A. Degiron, J. J. Mock, and D. R. Smith, “Modulating and tuning the response of metamaterials at the unit cell level,” Opt. Express **15,** 1115–1127 (2007).
11. D. A. Powell, I. V. Shadrivov, Y. S. Kivshar, and M. V. Gorkunov, “Self-tuning mechanisms of nonlinear split-ring resonators,” Appl. Phys. Lett. **91,** 144107 (2007).
12. M. W. Feise, I. V. Shadrivov, and Yu. S. Kivshar, “Tunable transmission and bistability in left-handed band-gap structures,” Appl. Phys. Lett. **85,** 1451–1453 (2004).
13. V. M. Agranovich, Y. R. Shen, R. H. Baughman, and A. A. Zakhidov, “Linear and nonlinear wave propagation in negative refraction metamaterials,” Phys. Rev. B **69,** 165112–165117 (2004).

#101650 - $15.00 USD Received 17 Sep 2008; revised 16 Nov 2008; accepted 21 Nov 2008; published 24 Nov 2008

14. I. V. Shadrivov, A. A. Zharov, and Yu. S. Kivshar, “Second-harmonic generation in nonlinear left-handed metamaterials,” J. Opt. Soc. Am. B **23,** 529–534 (2006).
15. A. K. Popov and V. M. Shalaev, “Compensating losses in negative-index metamaterials by optical parametric amplification,” Opt. Lett. **31,** 2169–2171 (2006).
16. S. Wen, Y. Wang, W. Su, Y. Xiang, X. Fu, and D. Fan, “Modulation instability in nonlinear negative-index material,” Phys. Rev. E **73,** 36617 (2006).
17. N. Lazarides, M. Eleftheriou, and G. P. Tsironis, “Discrete Breathers in Nonlinear Magnetic Metamaterials,” Phys. Rev. Lett. **97,** 157406–4 (2006).
18. Y. Liu, G. Bartal, D. A. Genov, and X. Zhang, “Subwavelength Discrete Solitons in Nonlinear Metamaterials,” Phys. Rev. Lett. **99,** 153901–4 (2007).
19. S. Feng and K. Halterman, “Parametrically Shielding Electromagnetic Fields by Nonlinear Metamaterials,” Phys. Rev. Lett. **100,** 63901–4 (2008).
20. A.B. Kozyrev, H. Kim, A. Karbassi, and D. W. van der Weide, “Wave propagation in nonlinear left-handed transmission line media,” Appl. Phys. Lett. **87,** 121109–3 (2005).
21. A. B. Kozyrev, H. Kim, and D. W. van der Weide, “Parametric amplification in left-handed transmission line media,” Appl. Phys. Lett. **88,** 264101–3 (2006).
22. A. B. Kozyrev and D. W. van der Weide, “Trains of envelope solitons in nonlinear left-handed transmission line media,” Appl. Phys. Lett. **91,** 254111-3 (2007).
23. M.W. Klein, M. Wegener, N. Feth, and S. Linden, “Experiments on second- and third-harmonic generation from magnetic metamaterials,” Opt. Express **15,** 5238-5247 (2007)
24. N. A. Zharova, I. V. Shadrivov, A. A. Zharov, and Yu. S. Kivshar, “Nonlinear transmission and spatiotemporal solitons in metamaterials with negative refraction,” Opt. Express **13,** 1291–1298 (2005).

Engineered microstructured metamaterials demonstrate many intriguing properties for the propagation of electromagnetic waves including negative refraction and negative refractive index. Such materials have been studied extensively during recent years (see, e.g., Ref. [1] and references therein). Typically, the metamaterials are fabricated as composite structures created by many identical resonant scattering elements with the size much smaller than the wavelength of the propagating electromagnetic waves. Such microstructured materials can be described in terms of macroscopic quantities– electric permittivity ε and magnetic permeability μ. By designing the individual unit cells of metamaterials, one may construct composites with effective properties not occurring in nature.

Split-ring resonators (SRRs) are the key building blocks for the composite metamaterials, in particularly the materials having the negative refractive index [2]. Recent theoretical studies have demonstrated how to tune dynamically the electromagnetic properties of metamaterials [3, 4, 5, 6, 7, 8] and the fabrication of nonlinear SRRs has been demonstrated by placing a varactor diode [9] or a photosensitive semiconductor [10] within the gap of the resonator. The diode allows the SRR element to be tuned by an applied dc voltage or by a high-power signal as was shown already in experiment [9, 11]. These recent advances open a way for both fabrication and systematic study of nonlinear tunable metamaterials which may change their properties and the transmission characteristics by varying the amplitude of the input electromagnetic field.

It was shown theoretically that nonlinear metamaterials can demonstrate many intriguing novel features such as unconventional bistability [3, 12], backward phase-matching and harmonic generation [13, 14, 15], modulational instability [16], discrete breathers [17] and subwavelength solitons [18], as well as parametric shielding of electromagnetic fields [19]. Some of these features have already been observed experimentally in nonlinear left-handed transmission lines which are model systems allowing for combining nonlinearity and anomalous dispersion [20, 21, 22]. Importantly, in such composite structures the microscopic electric fields can become much higher than the macroscopic electric field carried by the propagating electromagnetic waves. This provides a simple physical mechanism for enhancing nonlinear effects in the resonant structures. Moreover, an attractive goal is to create tunable metamaterials where the input field changes the structure enhancing or suppressing the wave transmission. The dynamic tunability, apart from the expected applications for power limiters, will also allow changing

#101650 - $15.00 USD Received 17 Sep 2008; revised 16 Nov 2008; accepted 21 Nov 2008; published 24 Nov 2008

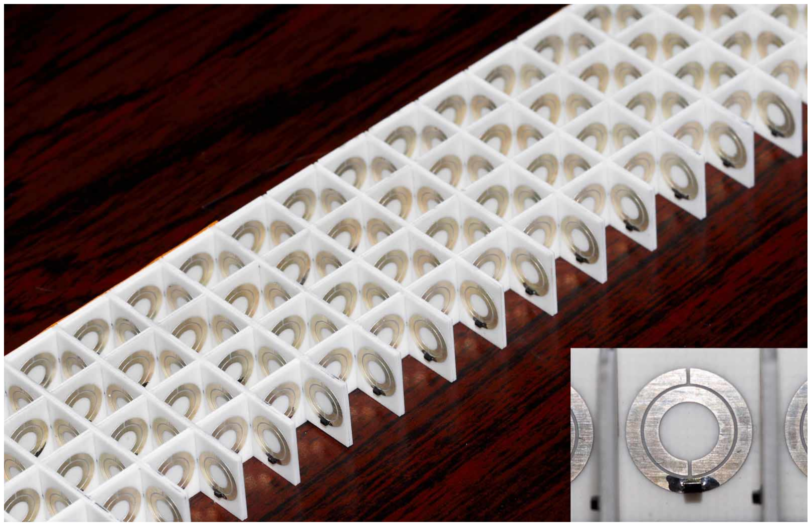

Fig. 1. Photograph of the nonlinear tunable magnetic metamaterial created by a square lattice of nonlinear SRRs. Each SRR contains a varactor which provides the power-dependant nonlinear response.

effective parameters of the same structure. This may be important for such narrowband composites as metamaterials, and it will increase accessible bandwidth of operation by tailoring the resonance with electromagnetic wave intensity.

In this paper, we report on the fabrication and experimental studies of the properties of the nonlinear tunable *magnetic metamaterial* operating at microwave frequencies. Such metamaterials are fabricated by modifying the properties of SRRs and introducing varactor diodes in each SRR element of the composite structure [9, 11], such that the whole structure becomes dynamically tunable by varying the amplitude of the propagating electromagnetic waves. In particular, we demonstrate the power-dependent transmission of the magnetic metamaterials at higher powers, as was suggested earlier theoretically [3], and we realize experimentally the nonlinearity-dependent enhancement or suppression of the transmission in dynamically tunable magnetic metamaterial.

Metamaterial sample (see Fig. 1) is fabricated from 0.5 mm thick Rogers R4003 printed circuit boards with nominal dielectric constant of 3.4. We make dielectric boards with the appropriate slot allocations with tin coated copper nonlinear SRRs. Photograph of one of several nonlinear metamaterial structures is shown in Fig. 1. Each SRR contains variable capacity diode (model Skyworks SMV-1405) which introduces nonlinear current-voltage dependence and results in nonlinear magnetic dipole moment to each SRR [11]. In terms of effective medium parameters, the manufactured structure has nonlinear magnetization and nonlinear effective magnetic permittivity [3]. Arrays of SRRs form a two-dimensional square lattice with 29x4x1 unit cells of the size of 10.5mm.

First, to identify the effect of the nonlinearity we measure the transmission properties of the tunable magnetic metamaterial for different values of the input power. To measure the electromagnetic field scattering for our samples, the metamaterial slab is placed in a parallel plate waveguide. The planes of SRRs are aligned perpendicular to the parallel plate surfaces. The input monopole antenna is placed at the midpoint of the lower plate, 2 mm from the metamaterial slab, in front of the central unit cell, and it consists of a teflon-coated conductor of 1.26 mm diameter and 11 mm long. The teflon coating provides a better energy coupling into

#101650 - $15.00 USD Received 17 Sep 2008; revised 16 Nov 2008; accepted 21 Nov 2008; published 24 Nov 2008

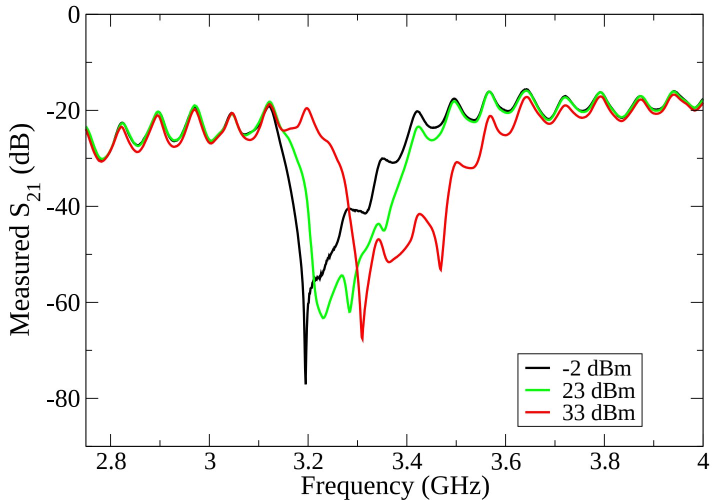

Fig. 2. Measured transmission parameter S_{21} detected by a monopole antenna behind the nonlinear magnetic metamaterial at different power levels indicated on the plot.

the waveguide for the wavelengths of interest. The antenna is positioned perpendicular to the bottom plate, so that the excited electric field is polarized perpendicular to the plane, and thus parallel to the wires. The magnetic field of the wave has mainly an in-plane component, effectively exciting the SRRs. Close positioning of the source antenna to the metamaterial was chosen in order to funnel high EM power into the metamaterial sample in order to observe nonlinear effects. We note that different positioning of the source antenna with respect to the central unit cell of the metamaterial gives slightly different quantitative results for the measured transmission, however qualitatively all the results are identical. This effect appears due to different antenna impedance matching to the sample. An identical antenna is placed in the center of the top plate, and is used as receiver for spectra measurements and for raster scan of the electric field distribution in the horizontal plane. The input antenna is excited using an Agilent E8364A vector network analyzer, which output is amplified by HP 83020A 38dB amplifier. For the spectra measurements, the receiving antenna is located 2cm behind the metamaterial slab, in front of the central unit cell of the metamaterial, and it is connected to the network analyzer as well. The measurements of the electric field inside the waveguide are evaluated in terms of the magnitude and phase of the transmission coefficient S_{21} between the input of the source and output of the receiver antenna. The measured transmission parameter S_{21} characterizes local electric field in the vicinity of the receiver antenna. Due to the two-dimensional nature of the parallel plate waveguide, as well as symmetry of our sample, the electric field in the scanned area is expected to remain polarized mainly perpendicular to the plane of the plates. Due to the polarization selection imposed to the waveguide, we are not able to observe any polarization-conversion effects in our setup, and further experiments with free-space measurements could expose new polarization effects, as was already indicated in [23].

We have performed a through calibration of our measurement setup up to the end of the feeding cables. The monopole antennas are strongly mismatched to the cables in order to obtain relatively flat wide band response. As a result, the absolute values for the measured transmission parameters are very low. In our configuration, the calibration of the setup using transmission through the empty waveguide does not seem to be meaningful, because adding metamaterial close to the monopoles will modify impedance of the antennas.

In order to analyze the power-induced shift of the magnetic resonance due to the action of

#101650 - $15.00 USD Received 17 Sep 2008; revised 16 Nov 2008; accepted 21 Nov 2008; published 24 Nov 2008

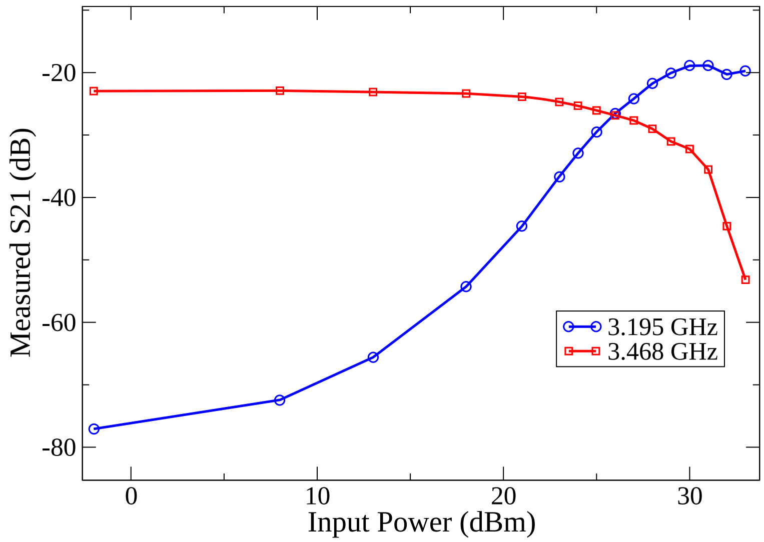

Fig. 3. Measured transmission parameter S_{21} detected by a monopole antenna as a function of incident power for two frequencies, demonstrating suppression and enhancement of transmission by a nonlinearity-induced shift of the magnetic resonance.

the varactor diodes introduced into SRRs, we measure the power detected by a receiver antenna behind the magnetic metamaterial for different values of the input power. Figure 2 shows the dependence of this power on the frequency at three different values of the input power. Similar to the nonlinearity-induced effects observed for a single SRR [9, 11], the resonant frequency is shifted to the right when the input power grows. These results show that, by selecting the operational frequency near the resonance, we may change dynamically the transmission properties of the metamaterial by varying the input power.

In the case of strong losses, the dependence of the local field detected by the receiver antenna on the amplitude of the incident field is smooth, since the hysteresis [3] is suppressed by losses. If we select the input frequency in the regime when the metamaterial is not transparent (at the low-frequency edge of the resonance, see blue curve in Fig. 3), a change of the input power will lead to a shift of the resonant frequency and an initially opaque composite metamaterial may become transparent with the growth of the incident field amplitude [24]. An opposite effect takes place on the right-hand side of the resonance, when initially transparent structure becomes opaque for high incident power, see red curve in Fig. 3.

Figure 4 demonstrates an example of such tunable transmission. Top figures show the distribution of the electric field behind the magnetic metamaterial slab at 3.2 GHz for low power of the source when the metamaterial is mostly opaque (Fig. 4 (a)), and for higher power when the metamaterial becomes transparent (Fig. 4 (b)). Thus, the material properties such as transmission can be switched from the reflection to transparency regime. The intensity of electromagnetic waves generated by the point source is non-uniform, so that a shift of resonances of individual SRRs is inhomogeneous inside the metamaterial structure. The SRRs closer to the source will experience stronger fields and thus it is expected that only the central part of the metamaterial becomes transparent. Our experimental results confirm this effect by revealing a narrow aperture of the beam emerging from the metamaterial (see Fig. 4 (b)).

In the same metamaterial sample we can observe the opposite effect when at the high-frequency side of the resonance the transmission is suppressed by the nonlinearity 4 (c,d).

#101650 - $15.00 USD Received 17 Sep 2008; revised 16 Nov 2008; accepted 21 Nov 2008; published 24 Nov 2008

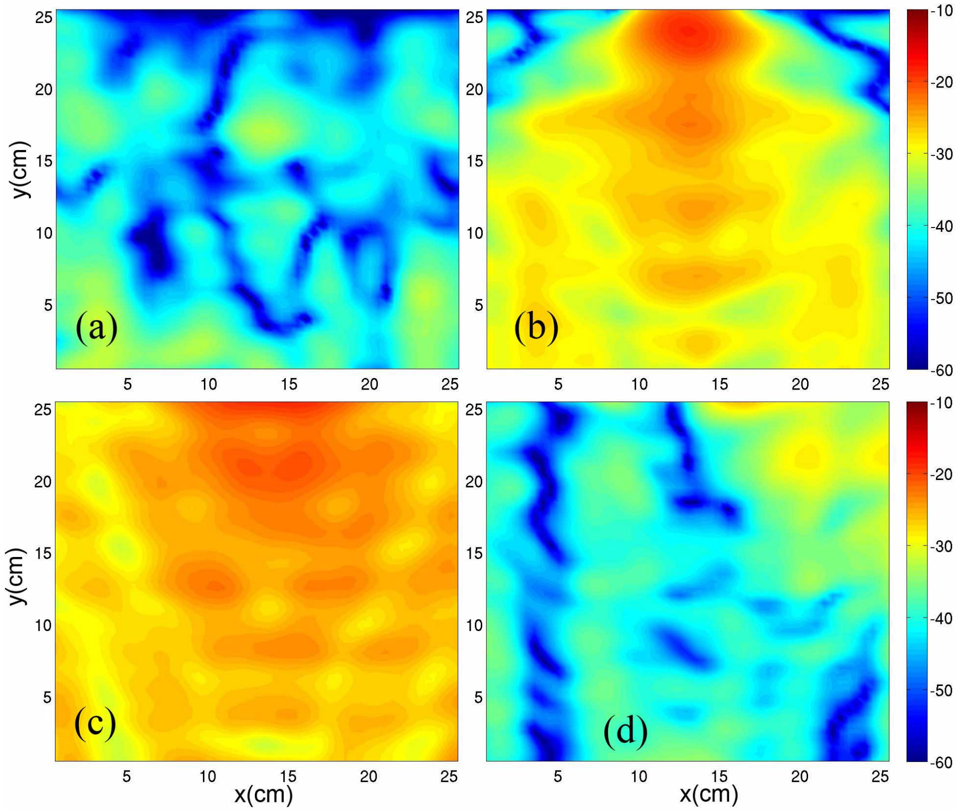

Fig. 4. Electric field distribution behind the magnetic metamaterial slab at 3.2 GHz for (a) low input power, 0dBm, and (b) high power, 30dBm; and 3.425 GHz for (c) low and (d) high power. The metamaterial slab and source are above the shown scanned area.

While the metamaterial is transparent for low powers (Fig. 4 (c)), the growth of the wave amplitude makes a part of the metamaterial opaque, and it prevents the radiation to go through the sample (see Fig. 4 (d)).

In conclusion, we have fabricated and analyzed the tunable nonlinear magnetic metamaterial operating at microwave frequencies. The microwave metamaterial is composed of split-ring resonators where each split-ring resonator has a varactor diode, and it can be tuned dynamically by varying the input power. We have shown experimentally that such nonlinear magnetic metamaterials demonstrate the power-induced shift of the magnetic resonance and nonlinearity-induced enhancement (or suppression) of the wave transmission. We believe our experimental results open a door for a systematic study of many intriguing novel features of nonlinear metamaterials earlier considered only theoretically for simplified models, as well as call for the effort to create such structures operating in the optical range.

Acknowledgment

Two of the authors (IS and YK) thank D. Powell, V. Shalaev, D. Smith, C. Soukoulis, and A. Zharov for useful discussions and suggestions. The work has been supported by the Australian Research Council, the Australian Academy of Science, and the Air Force Office of Scientific Research (AFOSR) through the MURI program (grant F49620-03-1-0420).