Extreme Subwavelength Magnetoelastic Electromagnetic Antenna Implemented with Multiferroic Nanomagnets

Justine Lynn Drobitch, Anulekha De, K. Dutta, Pratap Kumar Pal, Arundhati Adhikari, Anjan Barman, and Supriyo Bandyopadhyay*

Antennas typically have emission/radiation efficiencies bounded by $A/\lambda^2 (A < \lambda^2)$ where $A$ is the emitting area and $\lambda$ is the emitted wavelength. That makes it challenging to miniaturize antennas to extreme subwavelength dimensions without severely compromising their efficiencies. To overcome this challenge, an electromagnetic (EM) antenna is actuated with a surface acoustic wave (SAW) whose wavelength is about five orders of magnitude smaller than the EM wavelength at the same frequency. This allows to implement an extreme subwavelength EM antenna, radiating an EM wave of wavelength $\lambda = 2 \text{ m}$, whose emitting area is $A = 10^{-8} \text{ m}^2 \approx 2.5 \times 10^{-9}$, and whose measured radiation efficiency exceeds the $A/\lambda^2$ limit by over $10^5$. The antenna consists of magnetostrictive nanomagnets deposited on a piezoelectric substrate. A SAW launched in the substrate with an alternating electrical voltage periodically strains the nanomagnets and rotates their magnetizations owing to the Villari effect. The oscillating magnetizations emit EM waves at the frequency of the SAW. These extreme subwavelength antennas that radiate with efficiencies a few orders of magnitude larger than the $A/\lambda^2$ limit allow drastic miniaturization of communication systems.

1. Introduction

Many modern communication systems (cell phones, biologically implanted devices, radio frequency identification (RFID) systems, wearable electronics) will benefit immensely if antenna dimensions can be reduced to small fractions of the emitting wavelength. Miniaturizing antennas to extreme subwavelength dimensions, however, presents a significant challenge because the radiation efficiency is normally limited to $A/\lambda^2 (A < \lambda^2)$ where $A$ is the emitting area and $\lambda$ is the wavelength of the emitted radiation.[1-5] One approach to overcoming this limitation is to excite an electromagnetic antenna at acoustic resonance instead of electromagnetic resonance. Since the acoustic wave speed in many piezoelectric solids is roughly five orders of magnitude smaller than the speed of light in vacuum, the acoustic wavelength is five orders of magnitude smaller than the electromagnetic wavelength at the same frequency. Consequently, $A/\lambda_{\text{ac}}^2 \approx 10^5 \times A/\lambda_{\text{EM}}^2$, where $A$ is the radiating area of the antenna, $\lambda_{\text{ac}}$ is the acoustic wavelength, and $\lambda_{\text{EM}}$ is the electromagnetic wavelength at the same frequency. This strategy can increase the effective $A/\lambda^2$ limit on the radiation efficiency of an electromagnetic antenna by several orders of magnitude, and therefore it has been used to fashion extreme subwavelength antennas in the past.[6-10] In particular, Nan et al.[8] demonstrated an electromagnetic antenna, based on this principle, with $A/\lambda_{\text{EM}}^2 \approx 10^5$ and an efficiency of $\approx 0.4\%$. The efficiency exceeded the $A/\lambda_{\text{ac}}^2$ limit by a factor of $\approx 400$. This work[8] used a ferromagnetic bulk acoustic wave resonator (FBAR) which was excited acoustically and radiated electromagnetic waves at the resonator’s resonance frequency only. In contrast, our antenna is implemented with many magnetostrictive nanomagnets whose magnetizations oscillate when subjected to a surface acoustic wave (SAW). The SAW periodically strains the nanomagnets, making their magnetic moments oscillate in time owing to the inverse magnetostrictive (Villari) effect and emit electromagnetic waves. Thus, our antenna works on a different principle and employs a different structure. There are two advantages that our antenna has over the antenna of ref. [8]: First, we can exceed the $A/\lambda_{\text{EM}}^2$ limit by a much larger factor ($\approx 10^5$). Second, our antenna is not limited to a particular frequency (e.g., the resonance frequency of an FBAR). As long as the frequency is lower than the inverse of the time it takes for the magnetization vectors to rotate through a reasonably large angle, it can radiate at any arbitrary frequency (which would be the frequency of the SAW launched to activate the nanomagnets). Thus, our antenna can radiate over a wide range of frequencies. All of these antennas are, of course, distinct from conventional antennas where oscillating charges (not oscillating magnetic moments) excite electromagnetic waves.

In this work, we report the experimental demonstration of an extreme subwavelength EM antenna, based on the above principle, whose radiation efficiency exceeds the $A/\lambda_{\text{EM}}^2$ limit by a factor exceeding $10^5$. The antenna’s emitting area is more than eight orders of magnitude smaller than the square of the wavelength, resulting in drastic miniaturization. It consists of an
array of elliptical magnetostrictive (Co) nanomagnets of major axis dimension ≈360 nm, minor axis dimension ≈330 nm, and thickness ≈6 nm fabricated on a piezoelectric 128° Y-cut LiNbO3 substrate, thus forming a two-phase multiferroic (magnetostrictive/piezoelectric). A SAW is launched in the substrate with electrodes and the SAW periodically strains the nanomagnets, causing their magnetizations to oscillate in time owing to the inverse magnetostriction (Villari) effect. The oscillating magnetizations emit EM waves (at the frequency of the SAW), which are detected in the far field by a dipole antenna coupled to a spectrum analyzer. The SAW (excitation) frequency in our experiment was 144 MHz and we were able to detect EM emissions at the same frequency that was 8 dBm above ambient emissions, at a distance >2 m from the antenna. A control sample (that contained no nanomagnets, but was otherwise identical to the actual sample) was used for background subtraction. We were thus able to measure the EM emission from the nanomagnets at the exclusion of all other emitters (e.g., surface currents in the electrodes that are used to launch the SAW and any other spurious source radiating at or near 144 MHz). Based on the measured detected power and the input power to the SAW, we were able to infer that the electromagnetic radiation efficiency (ratio of power radiated by the nanomagnets to the input power to the SAW) is between 0.01% and 0.1%, which exceeds the $A/A_{\text{EM}}^2$ limit by more than five orders of magnitude.

2. Results

Figure 1 shows the scanning electron microscopy images of the nanomagnet arrays that we fabricated to realize the extreme subwavelength antenna. We made two sets of samples: Sample A and Sample B. The former contained 55 000 nanomagnets and the latter 275 000 nanomagnets. Figure 1a,b shows low-magnification images of several rectangular arrays in the two samples (each white speck is an array) and Figure 1c shows a zoomed image of one such array (where the magnification is not large enough to resolve individual nanomagnets). Figure 2 shows the nanomagnets at higher magnification that allows one to resolve individual nanomagnets and their dimensions.

The size of the nanomagnets was chosen based on our lithographic capability; we intended to make them as small as possible without losing control over their size or shape across an array of over 100 000 nanomagnets. We made the nanomagnets slightly elliptical so that they have thermal stability at room temperature, and yet not so elliptical as to make the shape anisotropy energy too large for the surface acoustic wave to budge their magnetizations from their stable orientations and emit electromagnetic waves. The shape anisotropy energy barrier within a nanomagnet is calculated from the formula in ref. [11] and found to be 10.2 eV ($=393 kT$ at room temperature). We would have been able to reduce it by reducing the lateral dimensions and thickness, or the eccentricity of the ellipses, but that deteriorates our control over the size and shape of the nanomagnets (reducing the thickness causes islanding) and was therefore avoided. Better lithography control might allow one to reduce the shape anisotropy energy barrier, resulting in more output power for the same input power.

We characterized the magnetic behavior of the nanomagnets with static longitudinal magneto-optical Kerr effect (S-MOKE) at room temperature using a He-Ne laser ($\lambda = 632 \text{ nm}$) having a focused spot size of $\approx 100 \mu m$. Figure 3 shows the Kerr rotation...
versus magnetic field characteristics (hysteresis loops) under two situations: when the magnetic field is directed along the horizontal axis of the arrays and when directed along the vertical axis. The hysteresis loops confirm that the fabricated nanostructures are ferromagnetic at room temperature. The coercivity is 100 Oe higher when the magnetic field is directed along the horizontal axis which is parallel to the minor axes of the elliptical nanomagnets.

It should be noted that the static MOKE measurements in Figure 3 do not sample a single nanomagnet, but an entire ensemble of nanomagnets since the spot size of the laser beam is ≈100 µm which covers 260 × 260 array of nanomagnets. Even though there is not much shape anisotropy in a single nanomagnet (major axis = 360 nm and minor axis = 330 nm), the array, however, is fairly anisotropic since the vertical edge-to-edge separation between neighboring nanomagnets is 65.5 nm while the horizontal edge-to-edge separation is 41.7 nm. Thus, there is considerable anisotropy in the inter-nanomagnet coupling. It is this anisotropy that is mainly responsible for the difference between the coercivities in the two directions.

In order to demonstrate the antenna function and also measure the antenna characteristics, we launched SAW signal in the substrate at two different frequencies ($f_{SAW} = 144$ and 900 MHz) and measured any detectable EM emission (above the noise floor determined by ambient emissions) at a distance >2 m from the samples. The detector was a dipole antenna calibrated to specific frequencies and these two frequencies belonged to that set, which is why they were chosen. We were able to detect EM emissions at 144 MHz, but not at 900 MHz which was too high a frequency for the magnetization of the nanomagnets to rotate through a sufficiently large angle. At 144 MHz, the EM wavelength is 2 m. Since the separation between the detector and the antenna was greater than the EM wavelength, we were measuring the far-field emission.

The SAW velocity in the LiNbO$_3$ substrate is about 4100 m s$^{-1}$,[12] and hence the SAW wavelength is 28.4 µm at 144 MHz, while the EM wavelength is 2 m at that frequency. The ratio of the SAW to EM wavelength is thus $1.42 \times 10^{-5}$.
We carried out the measurements for both samples A and B containing nanomagnets, as well as control samples that were otherwise identical to the real samples but had no nanomagnets. In Figure 4, we show the detection results at $f_{\text{SAW}} = 900$ MHz for Sample A (screenshots of the spectrum analyzer are shown in the Supporting Information). There is $\approx 1$ dB difference between the detected electromagnetic powers from the two samples showing that the nanomagnets are not radiating sufficiently at this frequency. Screenshots of the spectrum analyzer can be found in the Supporting Information. The input power to launch the SAW was 5 dbm (3.16 mW). The broad peak around 892.5 MHz is due to a spurious source in the measurement chamber that could not be isolated and removed.

![Figure 4](image)

Figure 4. The power spectra of electromagnetic emissions detected by a dipole antenna coupled to a spectrum analyzer when the SAW frequency is 900 MHz. The antenna is placed $>2$ m from the sample. The spectra are shown for Sample A and the control sample. There is only $\approx 1$ dB difference between the detected electromagnetic powers from the two samples showing that the nanomagnets are not radiating sufficiently at this frequency. Screenshots of the spectrum analyzer can be found in the Supporting Information. The input power to launch the SAW was 5 dbm (3.16 mW). The broad peak around 892.5 MHz is due to a spurious source in the measurement chamber that could not be isolated and removed.

We also carried out time-resolved magneto-optical Kerr effect (TR-MOKE) measurements on the nanomagnets at room temperature. Our past simulations of ideal nanomagnets have shown that strain-induced large angle magnetization rotation in single domain elliptical nanomagnets (of lateral dimension $\approx 100$ nm) typically takes place in about 1 ns.\textsuperscript{[11,13,14]} The nanomagnets used here are larger ($>300$ nm lateral dimension) and multidomain. Hence, it is possible that they rotate slower and therefore, the period of the 900 MHz signal (1.1 ns) does not allow them enough time to rotate through a sufficiently large angle and radiate electromagnetic waves. More importantly, the rotation can be impeded by defects and imperfections in the nanomagnets, which are known to affect the spin wave modes in them and the switching probability.\textsuperscript{[15,16]} Since these defects are random and unknown, we cannot simulate the time-domain dynamics of the nanomagnets' magnetizations in their presence and predict the switching time. Since we did not detect significant emission at 900 MHz, we reduced the excitation frequency to 144 MHz and the detection results are shown in Figure 5. We now clearly see a measurable difference between the real samples and the control sample. The detected radiation power from Sample B is 8 dB higher than that from the control sample, while that from Sample A is 3 dB higher than that from the control sample. These differences indicate that the nanomagnets are able to rotate their magnetizations sufficiently at this lower frequency and emit EM waves.

![Figure 5](image)

Figure 5. The power spectra of emissions detected when the SAW frequency is 144 MHz. Control 1 is the control sample corresponding to Sample A, and Control 2 is the one corresponding to Sample B. The input power was 5 dbm (3.16 mW). The detected emission from Sample B is 8 dB above that of Control 2 and is $-73$ dbm (50 pW).
temperature at various amplitudes of SAW excitation to verify that the launched SAW indeed has an effect on the magnetization rotation. The precessional oscillations in time-resolved Kerr rotations are measured with a TR-MOKE microscope based upon a two-color collinear pump–probe setup\cite{17,18} as shown in Figure 6a. The measurements were done in the absence of any bias magnetic field. The ultrashort laser pulses used in the TR-MOKE measurements set up very high frequency ($\approx 4$ GHz) oscillations of the nanomagnets' magnetizations\cite{17} and surprisingly, we found that the amplitudes of the Kerr oscillations resulting from these high-frequency oscillations are significantly increased by the launched SAW with $f_{SAW} = 144$ MHz. The amplitudes are markedly different in the absence of SAW versus in the presence of SAW. The amplitudes also show a rather weak dependence on the launched SAW power ($P$) for $P > -15$ dBm. These results are shown in Figure 6b,c for sample B. Note that the SAW frequency ($f_{SAW} = 144$ MHz) is more than an order of magnitude lower than the Kerr oscillation frequencies which are in the neighborhood of 4 GHz. The Kerr oscillations are not caused by the launched SAW. Instead, they are caused by the ultrashort laser pulses in the TR-MOKE setup. The excitation by the femtosecond laser causes an ultrafast demagnetization of the nanomagnets followed by two-step relaxation (not shown) which also launches an ultrafast internal field to trigger magnetization precession of the nanomagnets. The absence of any bias magnetic field ensures that the magnetization precesses around an effective magnetic field due to the dipolar coupling fields between the nanomagnets, which leads to a dominant natural resonance frequency at around 4 GHz. Clearly, the launched SAW strongly affects the amplitude of this resonant oscillation of magnetization despite being highly off-resonant (the SAW frequency is 144 MHz) and having a very weak SAW power. In Figure 6d, we show the fast Fourier transforms (power spectral densities) of the Kerr oscillations at launched SAW frequency of 144 MHz for various SAW power.

Figure 6. a) Schematic of the TR-MOKE microscope showing the pump and probe beams and the geometry of the measurement. The probe beam spot covers about four nanomagnets. b) The oscillations in time-resolved Kerr rotation in the absence of any externally launched SAW (top panel) and in the presence of an externally launched SAW at 144 MHz frequency with a power of $-15$ dBm (31.6 $\mu$W). The ultrashort laser pulses however independently induce high-frequency SAW waves in the substrate, which cause high-frequency oscillation of the magnetizations, leading to some Kerr oscillations. The oscillations are much more pronounced and have much larger amplitudes (before damping sets in) in the presence of the SAW. c) The oscillations in time-resolved Kerr rotations at various SAW power levels. The SAW frequency is 144 MHz, which is the frequency used in the antenna experiment. d) Power spectral densities of the Kerr oscillations at launched SAW frequency of 144 MHz for various SAW power.
is obviously quite complex and is reserved for future study (it is outside the scope of this paper).

In the TR-MOKE experiments, we cannot detect any Kerr oscillation shifting to the launched SAW frequency of 144 MHz because the time delay between the pump and probe laser ($\Delta t$) is limited to 3 ns and hence the lowest frequency component that can be resolved is about $1/3$ ns, i.e., 333 MHz. Therefore, we further launched a SAW of frequency $f_{\text{SAW}} = 350$ MHz. The time-resolved Kerr rotations and their fast Fourier transforms are shown in Figure 7a,b. In Figure 7b, we are still not able to detect any clear and consistent peak at 350 MHz. This indicates that either the SAW, by itself, cannot induce sufficient magnetization rotation at this high frequency of 350 MHz, or any signature of that rotation is being drowned by the much stronger Kerr oscillations caused not by the SAW, but by the ultrashort laser pulses. However, the clear observation that the SAW power affects Kerr oscillations unambiguously indicates that the SAW affects magnetization oscillations and thus could be the source of the electromagnetic emission which we observe.

### 3. Calculation of Antenna Radiation Efficiency

In Figure 8, we show the reflection coefficient $S_{11}$ (measured at the electrodes that launch the SAW) at the input power of 5 dBm (3.16 mW) as a function of frequency. The measurements are carried out with a network analyzer for Sample A, as well as for the control samples. At the frequency of 144 MHz, $\approx 85\%$ of the input power is reflected back to the source because of impedance mismatch and hence only about 15% of the input power is available to be coupled into the SAW. Therefore, the maximum actual power fed to the antenna via the SAW is $3.16 \times 0.15 = 0.474$ mW. This is the input power to Sample A, and the input power to Sample B is about the same.

The EM power from Sample B that is detected by the receiving dipole antenna is $\approx -73$ dBm (see Figure 5) which is about 50 pW. The power radiated by the control sample that is detected by the antenna is $\approx -81$ dBm, which is 8 pW. Hence, the power detected from the nanomagnets is 42 pW. The actual radiated power from Sample B is radiated over $4\pi$ solid angle and the fraction that is incident on the receiving dipole antenna (and hence detected) is $\frac{lw}{4\pi r^2}$ where $l$ is the length of the receiving antenna, $w$ is its width, and $r$ is the separation between the source and the detector. In our case $l = 2$ m, $w = 0.5$ cm, and $r = 2$ m. Hence, the ratio $\frac{lw}{4\pi r^2}$ is $10^{-4}$ and consequently, the power actually radiated by Sample B (over $4\pi$ solid angle) is $42 \times 10^4$ pW $= 0.42$ µW. Consequently, the radiation efficiency, which is the ratio of the radiated power to the input power, is $0.42$ µW/0.474 mW $= 0.088\%$ in the case of Sample B. In the case of Sample A, the detected power was $\approx -78$ dBm, which is about 15 pW. Therefore, the power from the nanomagnets in sample A that was detected by the antenna was $15$ pW $- 8$ pW $= 7$ pW. The radiated power was hence $7 \times 10^4$ pW $= 0.07$ µW. In this case, the efficiency is $0.07$ µW/0.474 mW $= 0.014\%$. Since Sample A had 55 000 nanomagnets and Sample B had 275 000 nanomagnets, we expect the radiation from Sample A to be weaker than that from Sample B, and we observed that to be the case.

Let us now calculate the $A/\lambda_D^4$ limit for both samples. The area of a nanomagnet is $\frac{\pi}{4} (a x b)$ where $a$ is the major axis dimension (360 nm) and $b$ is the minor axis dimension.
(330 nm). Since there are 55,000 nanomagnets in Sample A, the radiating area is \( A = \frac{\pi}{4}(360 \times 330) \times 10^{-18} = 5.5 \times 10^{-11} \text{m}^2 \). Hence, in the case of Sample A, \( \frac{A}{\lambda_{\text{EM}}} = 1.25 \times 10^{-4} \), which means that our measured efficiency of 0.014% was able to beat the \( A/\lambda_{\text{EM}} \) limit by 112,000 times. In the case of Sample B, the radiating area is \( A = \frac{\pi}{4}(360 \times 330) \times 10^{-18} = 275,000 \times 2.5 \times 10^{-11} \text{m}^2 \). Hence for Sample B, \( \frac{A}{\lambda_{\text{EM}}} = 6.25 \times 10^{-4} \), which means that our measured efficiency of 0.088% was able to beat the \( A/\lambda_{\text{EM}} \) limit by 140,800 times in Sample B.

4. Conclusion

In this work, we have demonstrated extreme subwavelength electromagnetic antennas whose radiation efficiencies greatly exceed the theoretical limit of \( A/\lambda_{\text{EM}}(A<\lambda_{\text{EM}}) \) [where \( A \) is the emitting area and \( \lambda_{\text{EM}} \) is the wavelength of the emitted electromagnetic wave] by a factor exceeding 10^5. This allows us to miniaturize electromagnetic antennas. In our case, the emitting areas of the antennas are about \( 2 \times 10^8 \) times smaller than the square of the emission wavelength. This drastic miniaturization was made possible by exciting the antennas at acoustic resonance instead of electromagnetic resonance. The surface acoustic waves were also found to amplify the magnetization response of these nanomagnets resonating in GHz frequency. This is for a low-frequency (long wavelength) antenna that is much smaller than the wavelength (so it can be implanted) and yet can radiate with acceptable efficiency that is well over the \( A/\lambda^2 \) limit. The antenna described here exceeds that limit by more than five orders of magnitude.

5. Experimental Section

Sample Fabrication: The electrodes for launching the surface acoustic waves have nearly rectangular shapes with lateral dimensions of \( \approx 2 \text{ mm} \) and were fabricated by optical lithography on a 128° Y-cut LiNbO₃ substrate. They are made of Au of thickness \( \approx 10 \text{ nm} \). Alignment marks were made for subsequent delineation of the nanomagnets. The substrate was then spin-coated with bilayer polymethyl methacrylate (PMMA) e-beam resists of different molecular weights to obtain good undercut: PMMA 950 also diluted 4% by volume in anisole, followed by PMMA 950 also diluted 4% by volume in anisole. The spin-coating was carried out at a spinning rate of 2500 rpm. The resists were subsequently baked at 110 °C for 5 min. Next, electron-beam lithography was performed using a Hitachi SU-70 scanning electron microscope (at an accelerating voltage of 30 kV and 60 Pa beam current) with a Nably NPGS lithography attachment. Finally, the resists were developed in methyl isobutyl ketone and isopropyl alcohol (MIBK-IPA, 1:3) for 270 s followed by a cold IPA rinse.

For nanomagnet delineation, a 5-nm-thick Ti adhesion layer was first deposited on the patterned substrate using e-beam evaporation at a base pressure of \( \approx 2 \times 10^{-7} \text{Torr} \), followed by the deposition of Co. The lift-off was carried out using Remover PG solution.

Measurements—Static Magneto-Optical Kerr Effect: The magnetic hysteresis loops of the sample were measured by a home-built 5-MOE magnetometer in the longitudinal geometry. A plane polarized continuous wave He-Ne laser of wavelength 632 nm was focused on the sample by lens assembly with spot size \( \approx 100 \mu \text{m} \). The sample was mounted on a high precision rotating mount in a variable magnetic field. The reflected beam was collected by a lens and sent to an optical bridge detector (OBD) for detection. The output signal from the OBD was then sent to a lock-in amplifier which works on phase-sensitive manner. To minimize the noise from signal the amplifier was fed with a reference signal of 50 kHz coming from a photoelastic modulator (PEM), kept in the path of the reflected beam. By sweeping the magnetic field the Kerr rotation was recorded. Here, hysteresis loops were measured for two different orientations of magnetization (\( \Phi = 0° \) and \( \Phi = 90° \)) by rotating the sample mount while keeping the magnetic field direction fixed.

Time-Resolved Magneto-Optical Kerr Effect: The ultrafast magnetization dynamics of the sample were measured by a home-built TR-MOKE effect microscope based upon a two-color collinear pump–probe setup. The second harmonic (\( \lambda = 400 \text{ nm} \), pulse width = 100 fs, spot size = 1 \( \mu \text{m} \)) of a Ti:Sapphire oscillator (Tsunami: Spectra Physics) was used to pump the sample, while the time-delayed fundamental laser (\( \lambda = 800 \text{ nm} \), pulse width = 80 fs, spot size = 800 nm) laser beam was used to probe the dynamics by measuring the polar Kerr rotation from the sample. A single microscope objective (N.A. = 0.65) was used to focus both the pump and probe beams collinearly on the sample surface. The back-reflected laser beams were collected by the same microscope objective and after filtering out the pump beam, the probe beam was directed to an OBD. The time-resolved reflectivity and Kerr rotation signals were separately measured by using the OBD ensuring no breakthrough of one into another. Two lock-in amplifiers were used to measure the signals from the OBD to detect the time varying Kerr rotation and reflectivity signals in a phase-sensitive manner. The pump beam was modulated at 2 kHz frequency by a mechanical chopper, which is used as the reference frequency of the lock-in amplifier. The sample was scanned by a piezoelectric XYZ stage to position the pump and probe beams at the desired location of the sample. This gives high stability to the sample in presence of feedback loops. RF signals \( f_{\text{RF}} = 144 \) and 350 MHz with varying powers from a signal generator (Rohde & Schwarz SMB 100A signal generator, frequency range: 100 kHz to 20 GHz) were launched on the sample by using standard probes through high-frequency and low noise coaxial cable (Model No. N1501A-203). All the measurements were performed at room temperature and in the absence of any external bias magnetic field.

Supporting Information

Supporting Information is available from the Wiley Online Library or from the author.

Acknowledgements

The authors are deeply indebted to Mr. Jonathan Lundquist for his help with obtaining the electromagnetic emission data and to Prof. Erdem Topsakal for his helpful suggestions with regard to the electromagnetic experiments. The work at Virginia was supported by a Virginia Commonwealth University Commercialization grant. Both institutions received support from an Indo-US Science and Technology Fund Center grant titled “Center for Nanomagnetics for Energy-Efficient Computing, Communications and Data Storage” (IUSSTF/JC-030/2018).
Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

J.L.D. fabricated all the samples and imaged them with scanning electron microscopy; A.D., K.D., and P.K.P. carried out the time-resolved magneto-optical Kerr effect measurements and analyses and A.A. performed the static MOKE measurements under the supervision of A.B. J.L.D. and J.L. carried out the electromagnetic measurements under the supervision of E.T; S.B. conceived of the experiments, supervised all measurements, analyzed the data, and wrote the manuscript, which was critiqued by all authors.

Keywords

extreme subwavelength electromagnetic antenna, nanomagnets, surface acoustic waves

Received: April 4, 2020
Revised: May 15, 2020
Published online: June 24, 2020

[1] B. A. Kramer, C.-C. Chen, M. Lee, J. L. Volakis, IEEE Antennas Propag. Mag. 2009, 51, 57.
[2] H. Mosallaei, K. Sarabandi, IEEE Trans. Antennas Propag. 2004, 52, 2403.
[3] A. K. Skrivervik, J. F. Zürcher, O. Staub, J. R. Mosig, IEEE Antennas Propag. Mag. 2001, 43, 12.
[4] J. P. Gianvittorio, Y. Rahmat-Samii, IEEE Antennas Propag. Mag. 2002, 44, 20.
[5] P. M. T. Ikonen, K. N. Rozanov, A. V. Osipov, P. Alitalo, S. A. Tretyakov, IEEE Trans. Antennas Propag. 2006, 54, 3391.
[6] Z. Yao, Y. E. Wang, S. Keller, G. P. Carman, IEEE Trans. Antennas Propag. 2015, 63, 3335.
[7] J. P. Domann, G. P. Carman, J. Appl. Phys. 2017, 121, 044905.
[8] T. Nan, H. Lin, Y. Gao, A. Matyushov, G. Yu, H. Chen, N. Sun, S. Wei, Z. Wang, M. Li, X. Wang, A. Belkessam, R. Guo, B. Chen, J. Zhou, G. Qian, Y. Hui, M. Rinaldi, M. E. McConney, B. M. Howe, Z. Hu, J. G. Jones, G. J. Brown, N. X. Sun, Nat. Commun. 2017, 8, 296.
[9] H. Lin, M. Zaeimbashi, N. Sun, X. Liang, H. Chen, C. Dong, A. Matyushov, X. Wang, Y. Guo, N. X. Sun, IMBioc 2018, 2018 IEEE/MTT-S Int. Microwave Biomedical Conf., IEEE, Piscataway, NJ 2018, pp. 13–15.
[10] H. Lin, M. R. Page, M. McConney, J. Jones, B. Howe, N. X. Sun, MRS Bull. 2018, 43, 841.
[11] M. Salehi-Fashami, K. Roy, J. Atulasimha, S. Bandyopadhyay, Nanotechnology 2011, 22, 155201.
[12] A. Holm, Q. Stürzer, Y. Xu, R. Weigel, Microelectron. Eng. 1996, 31, 123.
[13] K. Roy, S. Bandyopadhyay, J. Atulasimha, J. Appl. Phys. 2012, 112, 023914.
[14] A. K. Biswas, S. Bandyopadhyay, J. Atulasimha, Appl. Phys. Lett. 2014, 105, 072408.
[15] M. A. Abed, S. Sahoo, D. Winters, A. Barman, S. Bandyopadhyay, Sci. Rep. 2019, 9, 16635.
[16] D. Winters, M. A. Abed, S. Sahoo, A. Barman, S. Bandyopadhyay, Phys. Rev. Appl. 2019, 12, 034010.
[17] S. Mondal, M. A. Abed, K. Dutta, A. De, S. Sahoo, A. Barman, S. Bandyopadhyay, ACS Appl. Mater. Interfaces 2018, 10, 43970.
[18] A. Barman, J. Sinha, Spin Dynamics and Damping in Ferromagnetic Thin Films and Nanostructures, Springer International Publishing AG, Cham, Switzerland 2018.
[19] https://www.atlasrfidstore.com/rfid-insider/which-rfid-frequency-is-right-for-your-application (accessed: April 2020).
[20] https://www.etsi.org/technologies/radio/short-range-devices (accessed: January 2020).