IEEE Access
Multidisciplinary : Rapid Review : Open Access Journal

Received March 9, 2021, accepted May 21, 2021, date of publication June 2, 2021, date of current version June 9, 2021.

*Digital Object Identifier 10.1109/ACCESS.2021.3085301*

# Adaptation of Fluctuating Magnetoacoustic System to External Signals

**VLADIMIR L. SAFONOV[1], (Senior Member, IEEE), DEREK A. BAS[1], (Member, IEEE), DIANA BERMAN[2], YURI V. ROSTOVTSEV[3], JAMES A. ROBERTS[3], MICHAEL E. MCCONNEY[1], AND MICHAEL R. PAGE[1]**

[1]Materials and Manufacturing Directorate, Air Force Research Laboratory, Wright-Patterson Air Force Base, OH 45433, USA
[2]Department of Materials Science and Engineering, University of North Texas, Denton, TX 76203, USA
[3]Department of Physics, University of North Texas, Denton, TX 76203, USA

Corresponding author: Michael R. Page (michael.page.16@us.af.mil)

This work was supported by the Air Force Office of Scientific Research (AFOSR) under Award FA9550-20RXCOR074.

**ABSTRACT** The adaptation of systems to external influences is of broad interest. We study the influence of microwave signals of different shapes on the magnetoacoustic wave system with a giant nonlinearity in canted antiferromagnet $FeBO_3$ at room temperature, which is close to its phase transition to the paramagnetic state. The classical nonlinear system obeys external deterministic signals; the modulation response describes the shape of these signals. In response to a noisy spectrum, the system shows self-organization, and mode competition selects one excited mode while suppressing others. With an increase in the power of the external signal, another self-organization is observed in the form of a narrow peak at the frequency of the fundamental minimum. This represents the first observation of the macroscopic quantum statistical phenomenon, Bose-Einstein condensation of magnetoacoustic wave quanta in a wave system with a high level of thermal fluctuations. The resulting picture of adaptation can analogously be transferred to many other adaptive wave systems, including large scale adaptive wave systems in the natural environment.

**INDEX TERMS** Adaptation, Bose-Einstein condensation, fluctuations, magnetoacoustic, microwave signal, self-organization.

## I. INTRODUCTION

Adaptive systems encompass phenomena across many diverse environments and a wide range of sciences [1]–[3]. A general adaptive system model utilizes one or more levels of feedback, exhibits emergent properties and self-organization, and produces nonlinear dynamic behavior. Finding and studying different adaptation models increases the likelihood that similar fundamental principles can work in multiple areas of study, such as electronics, hydrodynamics, biology, etc. Here we study the adaptation of a system of magnetoacoustic waves (MAWs) in antiferromagnetic iron borate ($FeBO_3$) to external alternating magnetic fields as an extremely convenient and simple model with mathematical analogies in many other nonlinear wave systems. MAWs describe normal modes of coupled sound waves and spin waves in magnetoordered materials. Iron borate has a giant acoustic nonlinearity [4], and the magnetoacoustic wavelengths therein extend from the sample size to a fraction of a micron. Another important feature of our study is the proximity to phase transition to the paramagnetic state ($T_N = 348$ K), which creates a high level of fluctuations at room temperature; the average magnetic moments of the sublattices were about 40% of their values at zero temperature [5].

Two types of alternating fields were applied to the system, which we divide into microwave control signals and RF test signals. The amplitudes of the control signals were sufficient to induce nonlinear responses and system adaptation to external conditions. Weak test signals were used to probe the properties of the adapted system. We divided the control signals into types: a) deterministic field oscillations with a definite time sequence and b) noisy oscillation which can only be described statistically. The adaptation of the system is fundamentally different for each of these external conditions. When deterministic field oscillations were applied, the nonlinear system completely obeyed the deterministic action; the output waveform followed the input waveform. In contrast, when noisy oscillations were applied, the nonlinear

The associate editor coordinating the review of this manuscript and approving it for publication was Bing Li.

system self-organized leading to competition of modes and the excitation of only one mode. All these phenomena can be described within the framework of the classical wave formalism [6], [7].

With an increase in control signal power, the excitation of a nonlinear system enhances, and more complex adaptation was expected. However, we found that weak wave turbulence leads to energy flux down the spectrum and excitation of coherent vibrations at the lowest eigenfrequency of the sample. This is a quantum statistical effect known as quasi-equilibrium Bose-Einstein condensation (BEC) of MAW quanta at the fundamental minimum of the spectrum. Note that in contrast with the BEC of other quasiparticles [8]–[11], this represents the first observation in a wave system with a high level of thermal fluctuations near phase transition. Thus, we show that a macroscopic quantum phenomenon is observed in a system that appears to be classical in terms of both the excitation level and fluctuations.

## II. EXPERIMENT AND RESULTS

### A. SPECTRUM

The crystal $FeBO_3$ consists of two sublattices with magnetic moments oriented in opposite directions, almost compensating the total magnetic moment inside the material [5], [12], [13]. Iron borate has easy-plane anisotropy and a rhombohedral symmetry which is responsible for preserving the magnetic ordering in the material, leading to its high sensitivity to low-intensity signal variations. Due to Dzyaloshinskiĭ-Moriya interactions originating in iron borate [14], it exhibits weak ferromagnetic behavior.

The spectrum of MAWs can be written as [4]:

$$\omega_k \approx c_s k[1 - (\gamma H_\Delta/\omega_{sw,k})^2]^{1/2}, \tag{1}$$

where $c_s$ is the sound velocity, $H_\Delta$ describes the efficiency of linear interaction between magnetic and acoustic subsystems,

$$\omega_{sw,k} \approx \gamma[H_s(H_s + H_{DM}) + H_\Delta^2 + (\alpha k)^2]^{1/2}$$

is the frequency of the spin wave, $H_s$ is the static magnetic field, $H_{DM}$ is the Dzyaloshinskiĭ-Moriya field, and $\alpha$ is the non-uniform exchange constant.

The crystal sample of $FeBO_3$ was grown from the melted solution of iron borate [13]. The preferential orientation of the grown crystals is (111) which is also the magnetic plane of the crystal. The sample used in the study was of rhombus form with length of the side ~1.1 mm and thickness of ~0.1 mm (Figure 1A). The transverse sound speed is $c_s \approx 4.8 \times 10^5$ cm/s. The parameters $H_{DM} \approx 65$ kOe, $H_\Delta^2 \approx 0.7$ kOe$^2$ were obtained using FMR at room temperature.

### B. SAMPLE

The single crystal nature of the sample over the large scale has been additionally confirmed using Electron Backscattered Diffraction (EBSD) mode in FEI Nova 200 NanoLab Scanning Electron Microscopy (SEM). The images were collected in several places and compared for alignment of the lattice planes (Figure 1B).

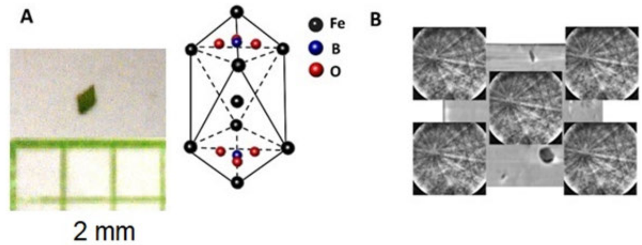



**FIGURE 1. A. The sample used in experiments is single crystal iron borate, having rhombohedral crystalline structure. B. EBSD analysis confirms single crystal nature of the samples.**

### C. INSTALLATION

We consider a simple and elegant system for observing a whole class of nonlinear wave phenomena (Figure 2A). The sample is placed inside a Teflon pocket and then inserted into the copper coil of the helical resonator (5 mm in diameter, 6-8 turns). Additionally, the sample was inside the RF signal generating coil (5 cm in diameter, 20 turns). The open helical resonator, which is a half-wavelength dipole, was excited by the microwave control signal $H_p(t)$. This signal was detected by the receiving antenna after absorption by the sample.

The coupling with an alternating magnetic field for MAWs in the sample of an easy-plane antiferromagnet $FeBO_3$ is large: $\partial\omega_k/\partial H \sim 10\gamma$. For comparison, such a coupling for spin waves in a ferromagnet is $\sim\gamma$. The microwave magnetic field $H_p \cos(\omega_p t)$ (control signal) parametrically excites [7], [15] a pair of waves with half of the pumping frequency $\omega_p/2 = \omega_k = \omega_{-k}$, and oppositely oriented wave vectors $\boldsymbol{k}$ and - $\boldsymbol{k}$. Pairs of MAWs were excited by the field of frequency $\omega_p/2\pi = 600 - 1000$ MHz at magnetic fields $H_s = 2 - 20$ Oe at room temperature.

The microwave signal (Figure 2C) is transmitted through the resonator, and when the sample is placed in the resonator the output is Figure 2D, which is nearly identical because the fraction absorbed by the small sample cross-section is negligible. Then an additional weak RF test field $H_m \cos(\omega_m t)$ was applied to the sample to modulate the MAW-based microwave absorption [16]. Below the pumping threshold, no changes in the spectrum were observed from the RF modulation. However, once the microwave field reaches the critical threshold value, parametric resonance initiated in the system results in MAWs at the mixed-signal frequencies which reradiate, leading to the appearance of satellites $\omega_p \pm \omega_m$ in the spectrum (Figure 2E). The satellites disappear if the external static magnetic field is increased to the value when the microwave field power cannot excite parametric resonance of MAWs due to their smaller coupling with the alternating field.

Signal mixing initiated via MAW parametric excitation by control signal was observed when additional modulation of the microwave field was applied. Figures 2F, G show a complex frequency-modulated microwave signal passed through the resonator and sample with the RF modulation field (test signal) turned off. In this case, the pump control frequency has a certain dependence on time $\omega_p(t)$ and

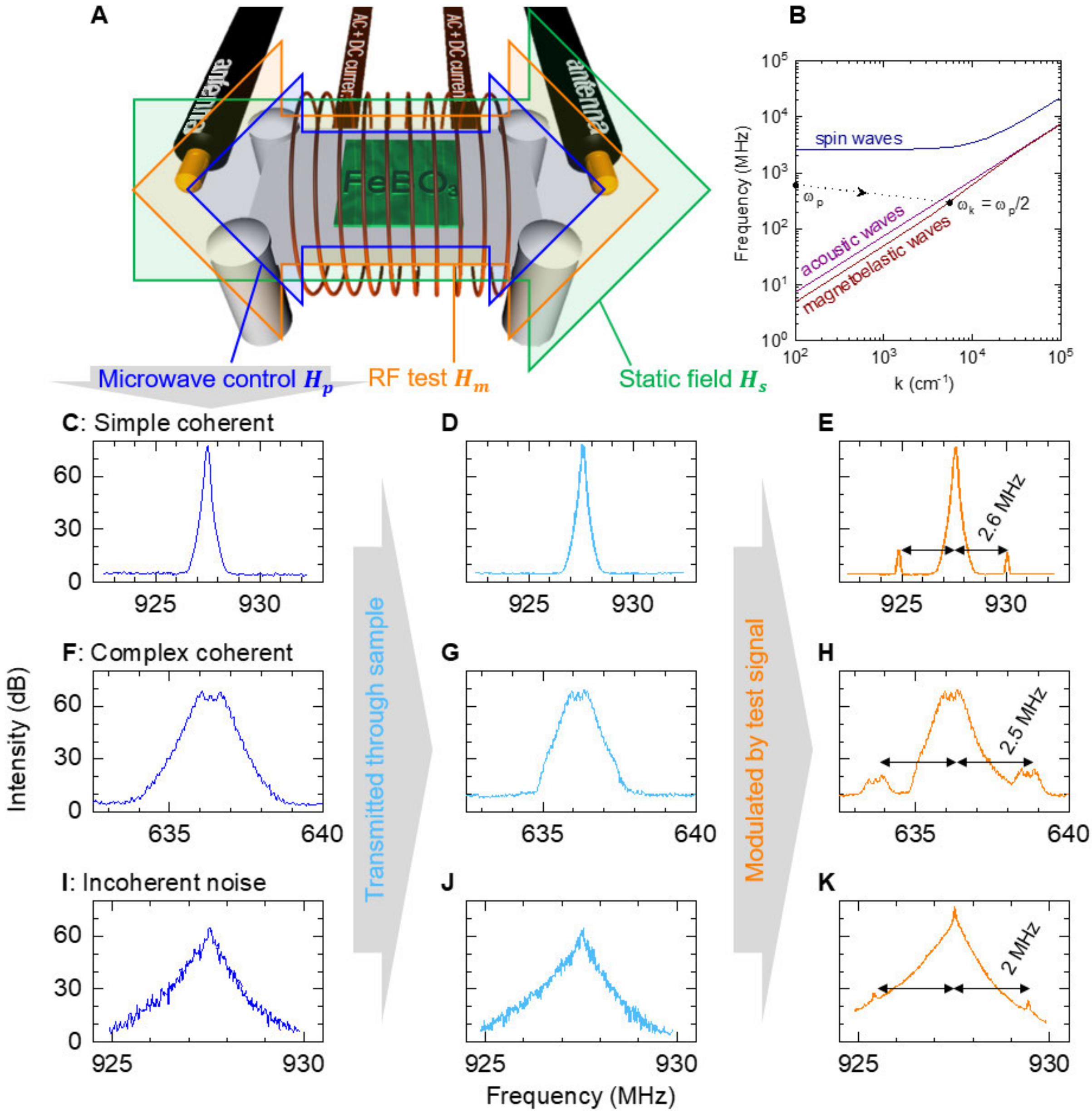



**FIGURE 2.** Control (microwave pump) signals transmitted through sample without RF modulation, and transmitted signals mixed with the RF test signal (RF modulation). A. Schematic showing the applied magnetic fields. B. Band diagram describing parametric excitation of magnetoacoustic waves ($H_s = 6$ Oe). C. Coherent pump at $\omega_p/2\pi = 927.4$ MHz as generated, D. transmitted through the sample, and E. after RF modulation $\omega_m/2\pi = 2.6$ MHz. F. Complex coherent pump with finite bandwidth (representing e.g. a radio station), centered at $\omega_p/2\pi = 636.2$ MHz as generated, G. transmitted through the sample, and H. after RF modulation $\omega_m/2\pi = 2.5$ MHz. I. Pump with phase noise to destroy coherence, centered at $\omega_p/2\pi = 927.5$ MHz as generated, J. transmitted through the sample, and K. after RF modulation $\omega_m/2\pi = 2.0$ MHz, time-averaged to make satellites visible. In all cases, absorption in the sample is negligible due to the small volume of the sample.

the transmitted signal describes the corresponding frequency band. Figure 2H shows the same signal with the RF test field turned on. In this case, the modulation response (left and right satellites) follows the form of the main signal $\omega_p(t) \pm \omega_m$. A similar pattern is observed with other deterministic microwave waveforms. Thus, the parametrically excited system of MAWs completely obeys the conditions of the microwave field experiencing no mode competition. We applied many different deterministic control signals to the system, and each time the modulation response reflected the shape of these signals.

The behavior of the system changed completely in the case of a non-deterministic microwave signal obtained as a result of the frequency noise modulation of the monochromatic microwave field. The transmitted noisy signal (Figures 2I, J) once the RF modulation is applied (Figure 2K) shows no scatter of the satellite frequencies; the observed satellites demonstrate a well-defined shape as if absorption occurs at

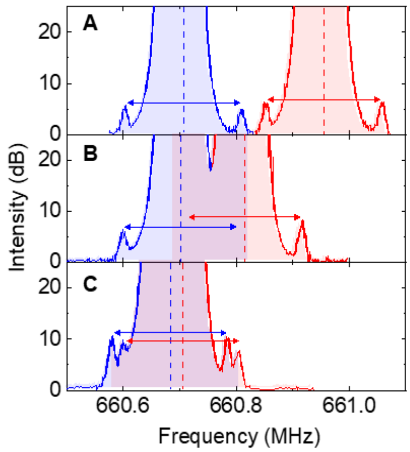



**FIGURE 3.** **Coexistence of modes proved by satellites. Independent pumps (control signals) with satellites as they overlap. Dotted lines indicate center frequencies of pumps, and arrows show satellite positions at ± 0.1 MHz from the centers. Colors are a visualization aid. A. Two independent pumps $P_1 = -4.8$ dBm, $P_2 = -2.06$ dBm with close frequencies (parallel pumping) $\omega_{p1}/2\pi = 660.95$ MHz, $\omega_{p2}/2\pi = 660.70$ MHz mixed with the test RF signal $\omega_m/2\pi = 0.1$ MHz. B. Two pumps with frequencies $\omega_{p1}/2\pi = 660.81$ MHz, $\omega_{p2}/2\pi = 660.70$ MHz mixed with $\omega_m/2\pi = 0.1$ MHz. C. Two pumps with frequencies $\omega_{p1}/2\pi = 660.72$ MHz, $\omega_{p2}/2\pi = 660.70$ MHz mixed with $\omega_m/2\pi = 0.1$ MHz. The difference 20 kHz between pump frequencies is observable by the difference between modulation responses.**

only one microwave frequency as in the case of monochromatic signal. This fact agrees with the result of [17] that radiation from a sample after a pulse of noise pumping is similar to specific radiation after a pulse of monochromatic pumping, in which only one group of waves is excited.

In the case of the noisy signal, the system chooses only one mode, indicating the presence of mode competition in the system. Similarly to noise-pumped laser systems [18], where competition arises from the fact that the dominant mode creates nonlinear damping thus suppressing other modes [19], a pair of MAWs parametrically excited in the resonator also creates nonlinear damping [20].

## D. MODE COMPETITION

To further explore the mode competition in the system of MAWs, using the test signal we analyzed the coexistence of two monochromatic microwave signals with similar frequencies and pumping powers. For this, two independent fields with a small difference in frequency values were introduced to the system. The frequency difference was further decreased while monitoring the mixed signals (Figures 3A, B, C). Despite the fact that each signal creates nonlinear damping that prevents the opponent to grow, both signals coexist and have RF satellites. The picture does not change with the convergence of frequencies (from A to B). Strikingly, in the case when the central lines almost merge completely (Figure 3C, the difference in frequency is ∼20 kHz), we see distinct satellites, indicating the coexistence of two independent signals. In other words, nonlinear mode attenuation is not a determining factor in mode competition when dealing with monochromatic signals. We observed the coexistence of up to 12 signals and their satellites.

Thus, we see that microwave signals with deterministic sources of different frequencies cause MAWs to coexist within the width of the resonator line. At the same time, with a noisy signal, the system of MAWs exhibits a self-organization by the mode competition. This adaptation of the magnetoacoustic system to external conditions manifested itself in a very wide range of microwave pumping power from −20 dBm to 15 dBm.

## E. BOSE-EINSTEIN CONDENSATION

For higher control signal power, we observed another effect of self-organization in the system, which we interpret as Bose-Einstein condensation of quanta of MAWs at the minimum frequency of the spectrum. This effect was most conveniently observed when the resonator and sample were rotated together at 45 degrees relative to the orientation of the static magnetic field (Figure 4A). Thus, the perpendicular ac field projection causes the formation of the instability onset leading to the momentary increase in the intensity needed for the condensate to form.

With increasing monochromatic power $P > P_c \approx -20$ dBm, stable absorption by MAW pairs was observed in the system until power reached $P_{me} \approx 16$ dBm. At still higher powers, sharply narrow satellites (quality factor $Q \approx 2.4 \times 10^8$) appeared with frequencies $\omega_p \pm \omega_{VM}$, where $\omega_{VM}/2\pi \approx 3$ MHz is a vibration mode (see Figure 4B: Satellite width here is limited to 100 kHz which is the resolution bandwidth of the measurement). The zoomed-in Figure 4C, taken with resolution bandwidth 10 Hz, shows the narrow linewidth (∼6 Hz) of the satellite. This measured width is limited by the instrument and may be even narrower. The most reliable data for this case was obtained at $H_s = 6.2 - 15$ Oe (Figure 4D). At the same time, the appearance of the lowest magnetoacoustic eigenmode line of the sample vibration with a frequency $\omega_{VM}$ was observed (Figure 4B). Note that the quality factor of the excited magnetoacoustic eigenmode line has increased by approximately 30-100 times compared to its value without pumping. Thus, we can suggest the observed phenomenon as BEC of MAW quanta, accumulated on the bottom of their spectrum. Despite the high level of thermal fluctuations, the system exhibits collective quantum statistical wave properties.

We observed a slow drift in $\omega_{VM}$ with a period of ∼1 minute, which can be explained by overheating. The $\omega_{VM}$ vibration and narrow satellites $\omega_p \pm \omega_{VM}$ existed up to our highest pumping power 30 dBm, after which overheating of the sample suppressed the condensate formation.

Figure 4D shows the dependence of the BEC frequency on the static magnetic field. The solid curve represents the theoretical field dependence of the magnetoacoustic eigenmode frequency. Note that the frequency of this oscillation $\omega_{VM}/2\pi \approx 3$ MHz is more than two orders of magnitude less than the pumping control signal frequency $\omega_p/2\pi \approx 900$ MHz. This means that the energy of parametrically

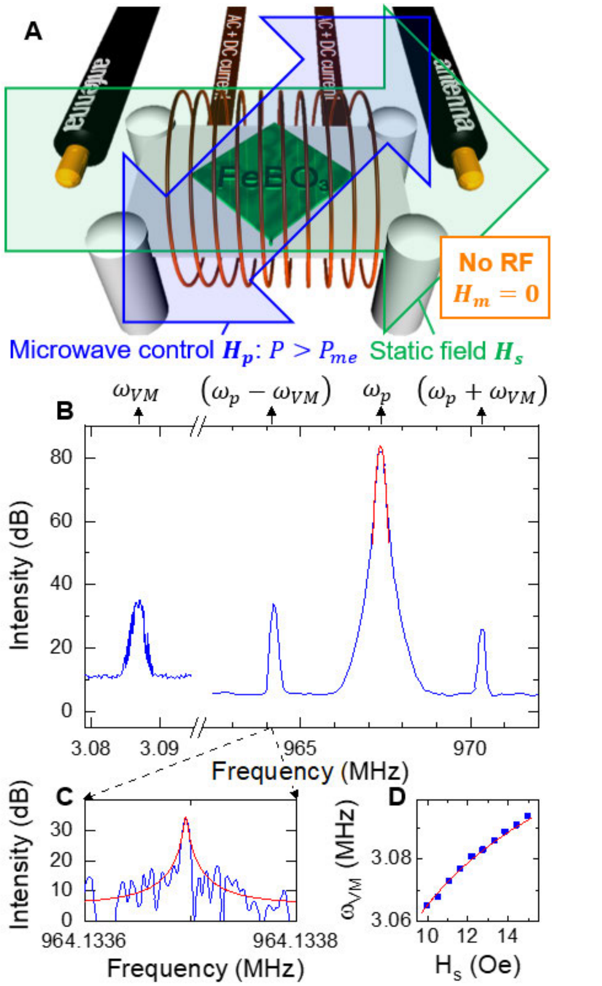



**FIGURE 4.** Room temperature Bose-Einstein condensation of magnetoacoustic quanta under conditions of strong fluctuations. A. Schematic showing the microwave pump control magnetic field and static magnetic field for suppressing the effects of external magnetic fields. Magnetoacoustic excitation occurs as a vibration in the easy magnetic plane of the sample. B. Control signal observed at $\omega_p/2\pi = 967.3$ MHz. BEC signal is observed at $\omega_{VM}/2\pi = 3.086$ MHz, and also produces satellites at $\omega_p \pm \omega_{VM}$. Blue curves are experimental data and the red curve is a Gaussian fit. Peaks at $\omega_{VM}$ and $\omega_p \pm \omega_{VM}$ appear to have width of ~100 kHz, which is the resolution bandwidth of the measurement. C. Satellite at $\omega_p - \omega_{VM}$ remeasured with narrower resolution bandwidth 10 Hz, showing $Q = 2.4 \times 10^8$ (compared to $Q = 7400$ for the pump control signal at $\omega_p$). D. Frequency of the vibration mode as a function of the applied static magnetic field. The red curve is theoretical dependence.

excited MAWs goes down the spectrum to a minimum until the critical accumulation leads to a macroscopic BEC in the form of a high-Q magnetoacoustic eigenfrequency vibration of the sample. The stability of this BEC is confirmed by the fact that the frequency $\omega_{VM}$ increases with increasing the pump power, i.e. the nonlinear MAW scattering amplitude is positive.

We further apply BEC to modulate complex microwave pumping signals (Figure 5). As expected, in Figures 5D and E, the modulation response describes the shapes of deterministic complex signals. It is interesting to note that if we add an RF modulation test field with $\omega_m/2\pi \approx 0.5$ MHz, then the

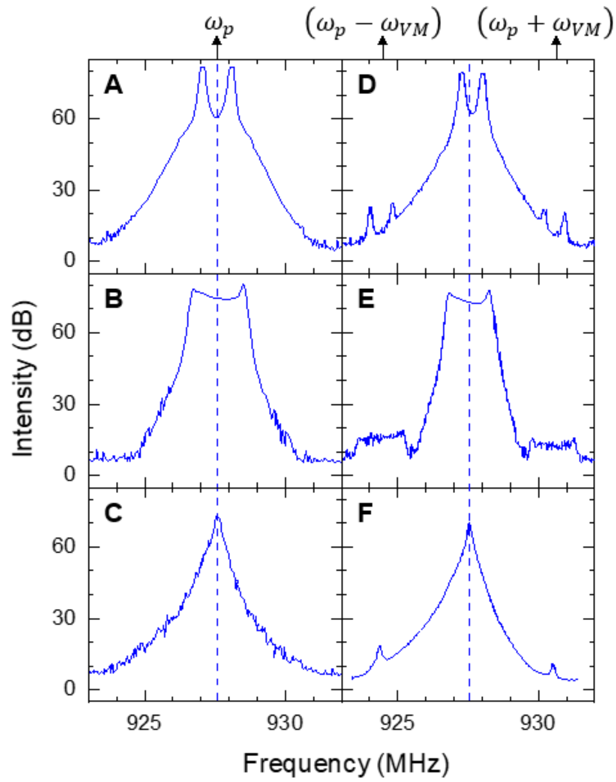



**FIGURE 5.** Bose-Einstein condensation-induced modulation of complex microwave control signals. Complex signals centered at $\omega_p/2\pi = 927.6$ MHz with no sample in place, with A. $P = 20.2$ dBm, $H_s = 9.8$ Oe, modulated via meander FM, B. $P = 19.9$ dBm, $H_s = 9.2$ Oe, modulated via sine FM, and C. $P = 20.5$ dBm, $H_s = 9.2$ Oe, with noise modulation. D, E, F. The same signals with the sample in place.

satellites from this field arise in the vicinity of the BEC frequency $\omega_{VM} \pm \omega_m$ and in the vicinity of BEC satellites $(\omega_p \pm \omega_{VM}) \pm \omega_m$. This means that all these states are condensates: macroscopic coherent states. In the case of noisy pumping, similar to the case for RF modulation, Figure 5F shows the response from a single signal of the winning mode as a result of mode competition with non-deterministic pumping on the wave system.

## III. DISCUSSION

Our research demonstrates very general adaptation properties of a nonlinear system of magnetoacoustic waves under conditions of strong fluctuations. The system obeys an external deterministic control signal, and with a noisy control signal it demonstrates self-organization by choosing only one excited mode. At a high level of excitation, self-organization occurs in the system by dumping excess energy to the bottom of the spectrum, where a macroscopic coherent state is excited: Bose-Einstein condensation of quanta of magnetoacoustic waves.

The high level of fluctuations in the system is an important feature in a broad array of disciplines. In one example, the characterization and control of ocean waves as a source of renewable energy is a recent topic of interest in the field of climate change [2]. Ocean waves are an abundant and energy-dense renewable resource which can be represented as a Fourier series or a broad spectrum. Their turbulent dynamics are modeled analytically and verified using buoy data with limited availability, and nonlinearity becomes increasingly relevant [21].

We also assume that there are analogies between the rogue or freak ocean wave generation [22] and the emergence of macroscopic quantum BEC of magnetoacoustic quanta in our system. Such large-scale systems of natural phenomena are challenging to study in situ, and therefore stand to benefit from having a simple tabletop analog in the convenience of a laboratory setting. With only a few simple off-the-shelf instruments, a wide variety of adaptive wave dynamics can be produced and rigorously examined, leading to improved control and understanding.

## ACKNOWLEDGMENT

Vladimir L. Safonov gratefully acknowledges the National Research Council for fellowship support. The authors would like to thank Meredith Irvin for valuable comments. This work was performed in part at the University of North Texas' Materials Research Facility.

## REFERENCES

[1] T. Carmichael, A. J. Collins, and M. Hadžikadić, *Complex Adaptive Systems*. Cham, Switzerland: Springer, 2019.
[2] G. Iglesias and J. Abanades, "Wave power: Climate change mitigation and adaptation," in *Handbook of Climate Change Mitigation and Adaptation*, W. Y. Chen, T. Suzuki, and M. Lackner, Eds. Cham, Switzerland: Springer, 2017, pp. 2007–2055.
[3] K. G. Vamvoudakis and S. Jagannathan, *Control of Complex Systems*. Amsterdam, The Netherlands: Elsevier, 2016.
[4] V. I. Ozhogin and V. L. Preobrazhenskiĭ, "Anharmonicity of mixed modes and giant acoustic nonlinearity of antiferromagnetics," *Sov. Phys. Uspekhi*, vol. 31, pp. 713–739, Aug. 1988.
[5] M. Pernet, D. Elmale, and J.-C. Joubert, "Structure magnetique du metaborate de fer $FeBO_3$," *Solid State Commun.*, vol. 8, no. 20, pp. 1583–1587, Oct. 1970.
[6] V. E. Zakharov, V. S. L'vov, and G. Falkovich, *Kolmogorov Spectra of Turbulence I, Wave Turbulence*. Berlin, Germany: Springer-Verlag, 1992.
[7] V. L. Safonov, *Nonequilibrium Magnons: Theory, Experiment and Applications*. Hoboken, NJ, USA: Wiley, 2012.
[8] S. O. Demokritov, V. E. Demidov, O. Dzyapko, G. A. Melkov, A. A. Serga, B. Hillebrands, and A. N. Slavin, "Bose–Einstein condensation of quasi-equilibrium magnons at room temperature under pumping," *Nature*, vol. 443, no. 7110, pp. 430–433, 2006.
[9] J. Klaers, J. Schmitt, F. Vewinger, and M. Weitz, "Bose–Einstein condensation of photons in an optical microcavity," *Nature*, vol. 468, no. 7323, pp. 545–548, 2010.
[10] K.-H. Bennemann and J. B. Ketterson, *Novel Superfluids*, vol. 1. New York, NY, USA: Oxford, 2013.
[11] A. V. Andrienko and V. L. Safonov, "Bose-Einstein condensation of mexons in hematite at +210° C," *Appl. Phys. Lett.*, vol. 115, Jul. 2019, Art. no. 012407.
[12] R. Diehl, W. Jantz, B. I. Noläng, and W. Wettling, "Growth and properties of iron borate, FeBO3," in *Current Topics in Material Science*, vol. 11, E. Kaldis, Ed. North-Holland, PR, USA, 1982, pp. 241–387.
[13] K. Seleznyova, "Magnetic properties and magnetic resonances of single crystals based on iron borate: Experimental studies and modeling," Ph.D. dissertation, Université de Bordeaux, Bordeaux, France, Dec. 2016.
[14] V. E. Dmitrienko, E. N. Ovchinnikova, S. P. Collins, G. Nisbet, G. Beutier, Y. O. Kvashnin, V. V. Mazurenko, A. I. Lichtenstein, and M. I. Katsnelson, "Measuring the Dzyaloshinskii–Moriya interaction in a weak ferromagnet," *Nature Phys.*, vol. 10, pp. 202–206, Mar. 2014.
[15] A. V. Andrienko, L. V. Podd'yakov, and V. L. Safonov, "Parametric excitation of magnetoelastic waves in single crystals of $CoCO_3$ and $FeBO_3$," *Sov. Phys. JETP*, vol. 74, no. 3, pp. 579–587, 1992.
[16] A. V. Andrienko, V. I. Ozhogin, V. L. Safonov, and A. Y. Yakubovskii, "Nuclear spin wave research," *Sov. Phys. Uspekhi*, vol. 34, no. 10, pp. 843–861, Oct. 1991.
[17] A. V. Andrienko and V. L. Safonov, "Observation of nonequilibrium Bose condensation of quasiphonons excited by a noisy microwave pump," *JETP Lett.*, vol. 60, pp. 464–469, Sep. 1994.
[18] G. Vemuri, K. V. Vasavada, and G. S. Agarwal, "Lasing without inversion in the absence of a coherent coupling field," *Phys. Rev. A, Gen. Phys.*, vol. 52, no. 4, pp. 3228–3230, Oct. 1995.
[19] R. Roy, A. W. Yu, and S. Zhu, "Quantum fluctuations, pump noise, and the growth of laser radiation," *Phys. Rev. Lett.*, vol. 55, no. 25, pp. 2794–2797, Dec. 1985.
[20] A. V. Andrienko and V. L. Safonov, "Nonlinear radiation damping of nuclear spin waves and magnetoelastic waves in antiferromagnets," *Phys. Rev. B, Condens. Matter*, vol. 93, no. 10, Mar. 2016, Art. no. 104423.
[21] J. Davidson and R. Costello, "Efficient nonlinear hydrodynamic models for wave energy converter design—A scoping study," *J. Mar. Sci. Eng.*, vol. 8, no. 1, p. 35, Jan. 2020.
[22] M. Onorato, S. Resitori, and F. Baronio, *Rogue and Shock Waves in Nonlinear Dispersive Media*. Berlin, Germany: Springer, 2016.

**VLADIMIR L. SAFONOV** (Senior Member, IEEE) received the M.Sc. degree in physics from the Moscow Institute of Physics and Technology, in 1978, the Ph.D. degree from the Kurchatov Institute of Atomic Energy, in 1984, and the D.Sc. degree from the National Research Center "Kurchatov Institute," Russia, in 1992. Since 1996, he has been working with Okayama University, Japan, and Toyota Technological University, Japan. From 1998 to 2005, he worked with the Center for Magnetic Recording Research, UCSD. Then, he worked for SeekTech Inc., Mag and Bio Dynamics Inc., and H2 Universe LLC. He currently has a fellowship from NRC at the Air Force Research Laboratory. He authored and coauthored more than 130 articles. He is the author of the book *Nonequilibrium Magnons* (Wiley-VCH). His main research interests include magnetic and magnetoelastic dynamics in ferro- and antiferromagnetic systems.

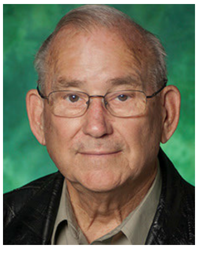
**DEREK A. BAS** (Member, IEEE) received the Ph.D. degree in physics from West Virginia University, in 2017. Since 2017, he has been a Research Physicist with Azimuth Corporation in the Functional Materials Division, Materials and Manufacturing Directorate, Air Force Research Laboratory, Wright-Patterson Air Force Base, OH, USA. His current interests include multiferroic materials, microwave communications, and ultrafast optics.

**DIANA BERMAN** received the B.S. degree in applied physics and math from the Moscow Institute of Physics and Technology and the Ph.D. degree in physics from North Carolina State University. Since 2012, she has been working as a Postdoctoral Researcher and a Research Associate with the Center for Nanoscale Materials, Argonne National Laboratory. In 2016, she joined the Materials Science and Engineering Department, University of North Texas (UNT), as an Assistant Professor. She is the author of more than 40 publications and six patents. Her research interests include synthesis and characterization of nanostructures, surfaces, and interfaces of ceramic and carbon-based materials for precise control and improvement of their physical properties and functionality. She was a recipient of the NSF Early Career Award, the UNT Presidential Early Career Professorship Award, the TechConnect National Innovation Awards at 2016, the 2017 Ralph E. Powe Junior Faculty Enhancement Award, and the 2017 TechConnect's Annual World Innovation Conferences and Expo.

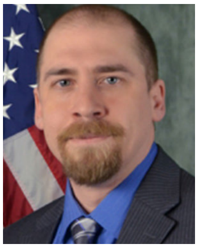
**YURI V. ROSTOVTSEV** received the master's degree from the Department of General and Applied Physics, Moscow Institute of Physics and Technology, Moscow, Russia, in 1983, and the Ph.D. degree from the Department of Plasma Physics and High Power Electronics, Institute of Applied Physics, Russian Academy of Sciences, Nizhny Novgorod, Russia, in 1991.

After working with the Institute of Applied Physics, Russian Academy of Sciences, since 1983, he moved to Texas A&M University, in 1996, where he received the NATO Postdoctoral Fellowship and later he became a TEES Research Professor, in 2004. In 2009, he moved to the University of North Texas, Denton, TX, USA, where he is currently working with the Department of Physics and the Centre of Nonlinear Sciences. He is also an Associate Professor of physics with the University of North Texas, known for his contribution to the quantum coherent effects in various media, ranging from atomic and molecular gases and solids to nucleus. He has published more than 200 articles in refereed journals. His research interests include atomic and molecular physics, laser spectroscopy, Raman spectroscopy, laser physics, quantum and nonlinear optics, free electron lasers, quantum thermodynamics, quantum information, quantum computers, nanoplasmonincs, nanophotonics, nanomaterials, super-resolution, and collective and cooperative excitations and phenomena.

Dr. Rostovtsev is a member of the Optical Society of America and the American Physical Society.



**JAMES A. ROBERTS** received the bachelor's and master's degrees from Louisiana Polytechnic University Physics, in 1958 and 1959, respectively, and the Ph.D. degree in experimental microwave spectroscopy from Oklahoma State University, in 1967. He currently studies the properties of liquids, particularly water, using microwave irradiation. He and his collaborators have discovered and studied second order phase transition of liquid water. His current research consists of probing of select materials using microwave spectroscopy as a tool and samples of materials containing nanoparticles are being explored with a goal to understanding shielding through the design of "smart skins" which can be used to shield electronic devices from damaging radiation and/or to act as shields against RADAR interrogation. This work is being conducted while working with teachers of science and mathematics to promote STEM education. This exposure to teachers to science projects is invaluable in promoting science in the area class rooms.



**MICHAEL E. MCCONNEY** is currently a Materials Scientist with the Functional Materials Division, Materials and Manufacturing Directorate, Air Force Research Laboratory, Wright-Patterson Air Force Base, OH, USA. He is active in optics, photonics, and novel anisotropic materials, including multiferroic materials. He has authored or coauthored 40 peer-reviewed articles, and his work has been cited over 2000 times. He is an expert in the mechanics and optics of anisotropic materials and thin-film physics.

**MICHAEL R. PAGE** received the Ph.D. degree in physics from The Ohio State University, Columbus, OH, USA. He is currently a Research Physicist with the Functional Materials Division, Materials and Manufacturing Directorate, Air Force Research Laboratory, Wright-Patterson Air Force Base, OH, USA. He performs research in the area of magnetic dynamics and high frequency electronics, and is developing hybrid multiferroic devices for novel agile RF electronics. He is an expert in magnetization dynamics and novel high frequency characterization techniques for investigating magnetic materials.