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Dynamic electromagnonic crystal based on artificial multiferroic heterostructure

Alexey B. Ustinov^{1*}, Andrei V. Drozdovskii^{1,2}, Andrey A. Nikitin^{1,3}, Alexander A. Semenov¹, Dmytro A. Bozhko^{2,4,5}, Alexander A. Serga², Burkard Hillebrands², Erkki Lähderanta³ & Boris A. Kalinikos¹

One of the main challenges for the modern magnonics, which, as opposed to the conventional electronics, operates with quanta of spin waves in magnetically ordered materials—magnons—is energy efficient control of magnon transport on small time and space scales. The magnon propagation in a time-dependent periodic spatial potentials—dynamic magnonic crystals—paves a way to this aim. To date, dynamic manipulation of the magnonic crystals has been realized with electric current and optic control influence. However, both approaches show limited potential for reduction in energy consumption and miniaturization of magnonic circuits. Voltage (or electric field) control of magnon currents promises to be fast and low energy consuming. It can be achieved in ferrite-ferroelectric (multiferroic) heterostructures, where strong coupling of magnons and microwave photons constitutes new quasiparticles called electromagnons. Here, we present an experimental realization of a voltage-controlled dynamic electromagnonic crystal operating with electromagnons at microwave frequencies.

¹Department of Physical Electronics and Technology, St. Petersburg Electrotechnical University, St. Petersburg, Russia 197376. ²Fachbereich Physik und Landesforschungszentrum OPTIMAS, Technische Universität Kaiserslautern, 67663 Kaiserslautern, Germany. ³Department of Physics, LUT-University, 53850 Lappeenranta, Finland. ⁴James Watt School of Engineering, University of Glasgow, G12 8LT Glasgow, United Kingdom. ⁵Department of Physics and Energy Science, University of Colorado at Colorado Springs, Colorado Springs, CO 80918, USA. *email: ustinov_rus@yahoo.com

As the very word indicates, the electromagnons are electro-active magnons. Historically, excitations arising from the coupling between the lattice and spin excitations in natural multiferroic solids like RMnO_3 ¹, $\text{Eu}_{0.75}\text{Y}_{0.25}\text{MnO}_3$ ², and Ni_3TeO_6 ³ are called electromagnons. Their counterparts exist in artificial multiferroics fabricated in the form of ferrite-ferroelectric layered structures. Indeed, an electrodynamic interaction between the high-frequency electromagnetic and spin waves in the multiferroic heterostructures leads to the formation of the hybrid spin-electromagnetic waves (SEWs)⁴. Quanta of these waves are electromagnons. Their spectrum is dually controllable by both electric and magnetic fields. By analogy to the known magnonic^{5–9} and photonic¹⁰ crystals, the multiferroic periodic heterostructures demonstrate band-gaps in SEW spectrum^{11–14}. Thus, we name them “artificial electromagnonic crystals”.

The multiferroic periodic heterostructures are usually fabricated as a combination of a magnonic crystal with a ferroelectric slab into a layered structure^{11–14}. A spatial periodicity of the different parameters of the thin magnetic film, constituting magnonic crystal, produces electromagnonic band gaps (EMBGs) in the SEW spectrum and modifies the SEW dispersion in the vicinity of the EMBGs. In practice, the spatial periodicity could be produced by different means, for example by variation of the thickness¹⁵, width¹⁶, and saturation magnetization¹⁷ of the magnetic film, as well as by modification of electrodynamic boundary conditions via a metal grating formed on the film surface¹⁸. Moreover, magnonic crystals can be created by periodic arrays of stripe domain structures¹⁹. These magnonic crystals have static properties, which are predefined by the fabrication and cannot be modified later. In contrast, the artificial electromagnonic crystals based on the static magnonic crystals provide possibility to dynamically change the EMBG frequency utilizing a bias electric field applied to the ferroelectric layer¹¹.

During the last decade the dynamic magnonic crystals (DMCs) started to attract more interest^{20–24}. Their distinct feature is a possibility to toggle on and off the spatial periodicity of the magnetic waveguide. This property allows one to realize the unusual microwave signal processing functions such as all-linear time reversal and frequency inversion of propagating wave packets²⁰. Most of them are controlled by electric current, which leads to generation of a waste heat. The more challenging, but more energy-efficient approach is to utilize the electric-field-controlled DMCs. So far, only a few theoretical studies have been performed on this subject^{25–28}.

Here we report on an experimental realization of the electric field control of the magnon current in the dynamic electromagnonic crystal (DEMC), which is based on the artificial multiferroic heterostructure. In contrast to other kind of the above-mentioned DMCs where spatial periodicity was realized by manipulations with the applied magnetic field, for the designed DEMC the spatially periodic waveguide properties are provided by a change in the properties of the adjacent ferroelectric layer. The spatial periodicity is achieved by a reduction of dielectric permittivity of the periodically poled regions of the ferroelectric layer by the applied local electric field.

Results

DEMC design. A schematic representation of the DEMC and the measurement cell are shown in Fig. 1. The multiferroic heterostructure composed of a rectangular Barium Strontium Titanate ($\text{Ba}_{0.5}\text{Sr}_{0.5}\text{TiO}_3$, BST) slab and an Yttrium Iron Garnet ($\text{Y}_3\text{Fe}_5\text{O}_{12}$, YIG) film constitutes the basis for one-dimensional DEMC (see Fig. 1a). The DEMC itself is a part of the YIG film waveguide contacted with the BST slab surface having Chromium metal grid

Fig. 1 Experimental dynamic electromagnonic crystal (DEMC) system.

a Sketch of a cross section of the DEMC. The DEMC comprises a grid electrode consisting of 10 100-nm-thick and 60-μm-wide stripes (5 shown), which are placed between 500-μm-thick Barium Strontium Titanate (BST) slab and 9.1-μm-thick Yttrium Iron Garnet (YIG) film on Gadolinium Gallium Garnet (GGG) substrate. Period of the grid Δ is 750 μm. Application of the electrical voltage U produces spatially periodic electric field inside the BST slab, distribution of which is shown as a color map. **b** Spatial distribution of the dielectric permittivity ϵ of the BST slab. **c** A top view of a fragment of the DEMC. **d** A measurement cell, which uses two microstrip antennas for excitation and reception of surface spin waves. The DEMC is located in the middle part of the YIG film between the antennas

electrode (see Fig. 1b, c). This prototype utilized 1-mm-thick and 8-mm-long BST slab, as well as 9.1-μm-thick and 40-mm-long YIG film (see Methods section for further details).

The measurement cell is fabricated in a form of a phase shifter (see Fig. 1d). The YIG film is longer than the BST slab in order to provide possibility for an effective excitation and reception of spin waves by 50 μm wide and 2 mm long short-circuited microstrip antennas. The antennas are fabricated on a grounded 500 μm thick alumina substrate. The distance between the antennas is 11.5 mm. Microstrip lines having impedance of 50 Ω are connected to the antennas. The measurement cell is magnetized by the uniform magnetic field H applied across the YIG waveguide along the antennas and grid electrodes in order to provide the conditions for excitation of magnetostatic surface spin waves (SSWs). The field is varied from 2000 Oe to 2300 Oe. The BST slab electrodes allow for application of a bias voltage in the range of $U = 0$ –1800 V.

Principle of operation and underlying physics. The measurement system operates as follows. The input antenna generates the SSW which propagates in the magnetic film towards the DEMC. Reaching the DEMC, the SSW converts into the SEW. Thus, the SEW propagates in the DEMC region. Further, the output antenna receives the SSW converted back from the SEW.

The physical mechanism underlying the control of the DEMC band gaps can be understood as follows. Initially, the multiferroic heterostructure without application of the control

voltage represents a spatially homogeneous waveguide for SEWs. Therefore, the electromagnon currents flow without backscattering as in a regular waveguide. We stress that the upper grid electrode is transparent for a microwave field of the SEW propagating in the structure and does not introduce any disturbance in their propagation. It was confirmed by measurements of the transmission characteristics of the DEMC. An application of a voltage to the grid electrode creates spatially periodic bias electric field across the BST slab. The distribution of this field is calculated and shown in Fig. 1a as a color map in real scale in accordance with the dimensions of the DEMC. The field causes the spatial periodicity of the polarization and of the value of dielectric permittivity of the BST slab.

The studied SEWs are formed as a result of hybridization of the surface spin wave mode (localized mostly in the magnetic film) with electromagnetic wave mode TE_1 (existing mainly in ferroelectric slab). A reduction in dielectric permittivity of the slab leads to an increase in group velocity of the electromagnetic mode. Thus, dispersion of the SEWs propagating in the multiferroic heterostructure depends on dielectric permittivity of the BST layer⁴. Under these conditions, initially excited SEWs having the Bragg wave vector $k_B = n\pi/\Lambda$ (where n is an arbitrary integer and Λ is a lattice constant) are coupled with the waves propagating in the opposite direction forming the electromagnonic band gaps at corresponding frequencies. Therefore, the periodic polarization of the BST slab leads to the periodic change in the wave guiding properties of the YIG-BST heterostructure and provides the rejection band in the amplitude-frequency characteristic of the investigated DEMC. Removal of the bias voltage transforms the DEMC back to a spatially homogeneous multiferroic waveguide.

Electric field control of the EMBG. We have performed numerical simulations of the dispersion characteristics of SEWs propagating in the DEMC. We used a theoretical model close to that developed in Ref. 25. First, the dispersion characteristics for SEWs propagating in the regular parts of the periodic waveguide were calculated using a theory reported in ref. 29. The experimentally determined dependence of ϵ on the applied voltage U was used in these calculations (see the Eq. 1 in Methods section). Then, the dispersion characteristics of the periodic structure were calculated using the transfer matrix method, which is widely used for the magnonic crystals³⁰. In the calculations, we assumed that the polarized regions of the ferroelectric slab are rectangular regions under elements of the grid electrode only.

Figure 2a, b show by solid curves the dispersion characteristics of the SEWs propagating in the DEMC and by dash-dotted curves the dispersion characteristics of the spin waves excited in the YIG film with the microstrip antenna. As is seen from the dispersion diagrams, the rejection band observed in the amplitude-frequency characteristics corresponds to the third electromagnonic band-gap. The used method of the SEWs excitation does not allow for observation of the first and the second electromagnonic band gaps because their frequencies are below the spin-wave cut-off frequency $\omega_p = 2\pi(\gamma H(\gamma H + \gamma 4\pi M_s))^{1/2}$.

Typical transmission characteristics and their fragments highlighting details of the dynamic properties of the multiferroic heterostructure are shown in Figs. 2c, d and 3a, b, respectively. It is clearly seen that an application of the bias voltage to the electrodes results in appearance of the pronounced rejection bands at the frequencies $f_{EMBG1} \approx 8.025$ GHz for $H_1 = 2106$ Oe and $f_{EMBG2} \approx 8.569$ GHz for $H_2 = 2293$ Oe where the transmission of SEWs is prohibited. A width of the rejection band is ≈ 1.5 MHz. Similar results were obtained for the other values of the bias field H .

Fig. 2 Experimental demonstration of the electromagnonic band-gap (EMBG). Dispersion characteristics of spin-electromagnetic waves are presented by solid curves for the bias magnetic fields $H = 2106$ Oe (a) and $H = 2293$ Oe (b). They confirm physical reason of well pronounced dips in transmission characteristics of the dynamic electromagnonic crystal (DEMC) (c, d) measured for the applied voltage $U = 1800$ V. It is clearly seen that the frequencies of the dips correspond to the third band-gap of the DEMC. In addition, the dispersion characteristics of spin waves shown in panels a and b by dash-dotted curves describe in good agreement the lower cut-off frequency of the measured amplitude-frequency characteristics and indicate impossibility to excite spin-electromagnetic waves below this frequency by the measurement cell. We will further call the dips on the transmission characteristics as rejection bands

The observed rejection band depth in decibels is almost a linear function of the applied voltage (Fig. 3c). An increase of U from 0 up to 1800 V leads to an increase in the depth from 0 to ≈ 5 dB. The depth is relatively small in comparison with the current-controlled DMCs²⁰ because this is the third rejection band, which is relatively narrow in comparison with the first, and the second bands. The results of numerical simulations, which will be considered further, demonstrate the quite narrow the third electromagnonic band gaps of ~ 1.5 MHz confirming our experimental observations.

The detailed analysis of the dispersion characteristics calculated for $H = 2106$ Oe shows that a strong coupling between the magnons and microwave photons takes place around the point of crossing the pure electromagnetic mode TE_1 and pure surface spin wave mode. The sign of strong coupling between the TE_1 and SSW is the large curvature of the upper and lower dispersion branches of the hybrid SEWs. The region of the strong magnon-photon coupling is marked in the Fig. 4a. We will consider the SEW lower branch because it is responsible for the observed DEMC performance. The electromagnons propagating in the DEMC within the frequencies of the strong coupling region have the maximum controllability by electric field. For the fabricated DEMC the first band gap (BG_1) is far below these frequencies (see Fig. 4b). It means that the first band gap is actually a photonic

Fig. 3 Voltage control of the electromagnon current at the frequency of electromagnetic band-gap (EMBG). Application of electrical voltage to the grid electrode leads to appearance of the rejection bands at the frequency of EMBG. The graphs show fragments of the transmission characteristics measured without applied voltage (solid curves) and for applied voltages of 950 V (dashed curves) and 1800 V (dash-dotted curves) for the bias magnetic field $H = 2106$ Oe (**a**) and $H = 2293$ Oe (**b**). The rejection depth increases with electric field almost linearly (**c**). The dynamic control of the electromagnon currents is observed for all values of the bias magnetic field in the range of $H = 2000$ – 2300 Oe

Fig. 4 Analysis of the band-gaps in the experimental dynamic electromagnetic crystal (DEMC). **a** Calculations of the dispersion branches of the electromagnetic mode TE₁, surface spin wave (SSW) mode and spin-electromagnetic wave (SEW) modes for $U = 0$ V. **b** Calculations of the lower branch dispersion characteristic of SEWs propagating in the DEMC for $H = 2106$ Oe and $U = 1800$ V demonstrate two band gaps BG₁ and BG₂ below the cut-off frequency and the band-gap BG₃ above it. **c** SEW dispersion near BG₂ in expanded scale calculated for the voltages $U = 0$ V (dashed curve) and $U = 1800$ V (solid curve). **d** SEW dispersion near BG₃ in expanded scale calculated for the $U = 0$ V (dashed curve) and $U = 1800$ V (solid curve). **e** Voltage control of the SEW dispersion showing an emergence of the band-gap. **f** Similar calculations for $H = 2293$ Oe. The small up-frequency shift is due to an increase in the group velocity of electromagnetic waves with a reduction in dielectric permittivity ϵ of the Barium Strontium Titanate (BST) slab. The dash-dot-dotted curves in **b**, **c**, and **d** show, for the sake of comparison, the SEW dispersion calculated for the case, when the voltage $U = 1800$ V is applied to the BST uniformly

band gap because the electromagnetic waves propagate in the multiferroic heterostructure below 6.5 GHz, and, therefore, they are not affected by the gyrotropic properties of the magnetic film. The second band gap (BG_2) is close to the region of the strong magnon-photon coupling (see Fig. 4c). Therefore, the BG_2 is the electromagnonic band gap having a width of ~ 2.5 MHz. The third band gap (BG_3) is relatively far from the strong coupling region (see Fig. 4d). At the same time, our experiments demonstrated the well-pronounced electric field control of the wave propagation. It confirms that the eigen excitations are electromagnons and that a relatively weak magnon-photon coupling exists in the multiferroic heterostructure near the frequency of the BG_3 . Therefore, the BG_3 has also EMBG nature.

Figure 4e shows that an increase in the applied voltage leads not only to an increase in the rejection band depth but also to its small frequency shift. We did not observe this shift in our measurements (Fig. 3). This discrepancy could be explained by the real distribution of the electric field in the ferroelectric layer which reduces dielectric permittivity ϵ effectively only in the regions around each element of the upper electrode, as is shown in Fig. 1c. This reduction in ϵ is not sufficient for experimental observation of the EMBG frequency shift. However, it is enough for appearance of the EMBG. The similar results were obtained for $H = 2293$ Oe (see Fig. 4f).

Note, that in consistency with tradition we use the standard term “band-gap” in order to distinguish frequency zones on the dispersion characteristic, which corresponds to rejection bands. The real band-gap with a finite frequency jump at the border of the Brillouin zone can be formed only in an idealistic loss-less artificial crystal. In a real-life lossy case, the dispersion relations remain continuous and the band-gap zone is characterized by a steeper slope, which results in a local increase in the group velocity of spin waves³¹. Detailed description of this dispersion peculiarity is published in refs. 32,33.

Discussion

Although the presented here DEMC has relatively large dimensions and requires an application of the large voltage of 1800 V, it is more efficient than the other proposed methods of dynamic control of the spin-wave band structure^{20,21} since the electrical power is required only when switching the electric field on or off. After a miniaturization of the magnetic film waveguide discussed widely in the previous works (see refs. 34,35) and the use of thin ferroelectric film with a slot transmission line^{36–38} the control voltage can be drastically reduced. For example, if we reduce size of the YIG film down to already reported in ref. 35 (the film thickness equals 100 nm and the waveguide width equals 5 μm), reduce the BST film thickness down to 1 μm , and produce a slot line along the YIG-film waveguide having a width of the slot of 5 μm (i.e., equal to the width of the magnetic film waveguide), then we obtain the control voltage of 1.8 V producing the same electric field across the ferroelectric film. Note, that the realization of the voltage control of the perpendicular magnetic anisotropy in the reconfigurable magnonic crystals²⁶ and in the logic devices²⁸ require to produce an electric field of 100–500 V/ μm . In contrast, the presented here DEMC requires only 1.8 V/ μm .

For DEMC the change in dielectric constant ϵ of BST slab is symmetric with respect to the sign of applied electric field E and is described by a quadratic function of E (see Fig. 5). As a result, the value of ϵ can be reduced only. Therefore, it is enough to apply voltage to the BST slab in one direction that simplifies demands to the DEMC voltage supply. For voltage-controlled magnonic crystals based on electric field controlled perpendicular magnetic anisotropy (PMA) the change in the PMA is a linear function of E ^{39–41}. As a result, the value of PMA can be both increased and

Fig. 5 Characterization of the Barium Strontium Titanate slab. Relative dielectric permittivity of $\text{Ba}_{0.5}\text{Sr}_{0.5}\text{TiO}_3$ ceramic as a function of bias electric field. The black squares are experimental data and the red solid curve is fitting result. The inset shows the ferroelectric slab for the dielectric permittivity measurement

reduced. Thus, the control of PMA is more flexible but demand more complicate voltage supply configuration.

One more step in the DEMC miniaturization can be realized through utilizing the ferroelectric films with large dielectric permittivity, for example, the potassium tantalate niobate ($\text{KTa}_x\text{Nb}_{1-x}\text{O}_3$) having $\epsilon > 20,000$ at the room temperature⁴². Our numerical simulations show that the maximum magnon-photon coupling occurs at about 100 rad/cm in the described above all-thin-film multiferroic heterostructure. Moreover, the slot transmission line allows for further reduction of the slot line width down to 1 μm . It shifts the maximum coupling to 150 rad/cm and overall electromagnon spectrum stretches for more than 400 rad/cm. Therefore, the use of grid electrode with the spatial period of $\Lambda = 10 \mu\text{m}$ should allow for the dynamic manipulation with electromagnons of $\lambda = 20 \mu\text{m}$, corresponding to the SEW wavenumber of $k \approx 314$ rad/cm. As a result, the DEMC will have the length of 100 μm (considering 10 periods of the electrodes grid), that is almost two orders of magnitude less comparing with known YIG-BST structures.

A switching time between on and off state depends mainly on the capacitance of the structure. This is a time of charging and discharging of the capacitor formed by the control electrodes and dielectric between them. The switching time in the investigated DEMC was on the order of hundreds of microseconds that is typical for the layered structures with a thick ferroelectric layer⁴³. This is relatively large value for the modern logic circuits. No attempts to decrease the switching time of the proposed device prototype have been made in our current studies. The switching time reduction is an engineering task which goes along with the idea of miniaturization of the DEMC and the use of the all-thin-film multiferroic heterostructure based on the slot line with “transparent” grid control electrodes. Taking into account the above-described geometry our estimates show a reduction in switching time below one nanosecond. This is typical value for a thin-film ferroelectric varactor capacitor⁴⁴.

The DEMC could offer a host of promising features: small size, small energy consumption, and fast operation. The use of the magnon-photon interaction opens a possibility to control the magnon currents by electric field in magnonic circuits through formation of the electromagnons in the regions where the magnonic waveguide is in contact with the ferroelectric film. The utilization of metallic magnetic spin-wave waveguides for the creation of the proposed electromagnonic crystal would lead to further miniaturization and increase in the switching speed. The realized technology is suitable for a fast switching of the crystal, allowing for the realization of all-linear time reversal and related spectral transformation phenomena²⁰. Thus, the presented

dynamic artificial electromagnonic crystal constitutes a novel basis for future magnonic circuits.

Methods

Ferroelectric slab fabrication. The ferroelectric layer was fabricated using a ceramic Barium Strontium Titanate (BST) slab. A BST blend was synthesized from the barium and strontium carbonates and titanium dioxide powders. Anatase-type titanium dioxide was used because it has the lowest surface free energy that obtain stability at small particle sizes⁴⁵. A ratio of the cations of rare-earth metals and titanium was maintained in order to obtain the composition $\text{Ba}_{0.5}\text{Sr}_{0.5}\text{TiO}_3$. The carbonates of the corresponding rare-earth metals and titanium dioxide were mixed and milled in a planetary ball mill at a speed of 800 rpm for 10 minutes with a reverse in isopropyl alcohol suspension. The mixture of the fine-dispersed raw materials was heated in a furnace at 1400 °C for 1 h. The rates of heating and cooling were 275 °C per hour. The synthesized BST blend was milled in the planetary ball mill one more time. After that, the BST slab was formed by a hydraulic press with pressure of 7.85 GPa and subsequent annealing at 1400 °C for 1 h with similar heating and cooling rates of 275 °C per hour. As a result, we obtained the BST slab of relatively large thickness and in-plane dimensions and polished it down to the thickness h of 1 mm.

Ferroelectric slab characterization. The samples of rectangular and disc shapes were cut from the large slab. The obtained disc slabs of the 4 mm radius were used for the BST characterization. The copper electrodes with the thickness of 2 µm were deposited on the both surfaces of the disc slabs by a vacuum evaporation technique in order to form a parallel plate capacitors. The capacitance-voltage characteristics and dielectric loss $\tan\delta$ were taken at the frequency of 1 MHz. An automated digital bridge (with a relative capacitance measurement error of 0.01%) was used to measure the impedance of the capacitor. The amplitude of the probing signal of the bridge was 1 V, the bias voltage was varied within $U = 0\text{--}1800$ V.

We have found that the $\tan\delta$ was 8×10^{-4} . The relative permittivity ϵ was calculated from the capacitance of the sample measured at the room temperature. Dependence of dielectric permittivity on bias electric field E is shown in Fig. 5. These data can be precisely fitted by the following expression:

$$\epsilon = 1266 - 39.5E^2(\text{kV/mm})^2. \quad (1)$$

As we expected for an isotropic dielectric ceramic material, the dielectric permittivity was a quadratic function of E . The obtained dependence is necessary for the numerical simulations of the spectrum of electromagnons in the periodic multiferroic heterostructure. Dependence of ϵ on applied voltage U can be easily calculated with substitution $E = U/h$.

It is worth mentioning that the solid BST does not exhibit any dispersion of the relative permittivity ϵ in a vast frequency range of $10^2\text{--}10^{11}$ Hz^{46,47}. Therefore, the values of ϵ obtained from Eq. (1) could be used in the microwave frequency range although they were measured at 1 MHz.

Grid electrode deposition. The rectangular BST slab had the in-plane dimensions of 6×8 mm. It was used for fabrication of the ferroelectric layer of the DEMC. The chromium electrodes with thickness of 100 nm were deposited on the both surfaces the BST slab by vacuum evaporation technique. Such a thickness for the chromium was much smaller than the skin depth for microwave frequencies below 10 GHz. Therefore, the electrode between the YIG and BST was transparent for the microwave radiation. The electrode on the bottom side of the BST was solid.

In order to provide the spatially periodic polarization of the BST slab, the top electrode was a grid consisting of 10 chromium (Cr) strips (see Fig. 1). The grid was fabricated by means of photolithography and wet-chemical etching. The period of the grid was $\Lambda = 750$ µm. The width of the metal strip was 60 µm. The strips were short-circuited along the long edge of the BST slab.

YIG film fabrication. The ferrite layer was fabricated from the Yttrium Iron Garnet (YIG) film. The YIG film was grown on 500 µm thick Gadolinium Gallium Garnet (GGG) substrate by liquid-phase epitaxy. The spin-wave waveguide structures of 2 mm width were cut from the YIG/GGG wafer. The waveguide of a good quality was chosen using the “magnetic well” technique. The technique is based on the localization of the microwave magnetization oscillations in the ferrite film. The localization occurs due to the spatial inhomogeneity of the bias magnetic field⁴⁸. This technique provides the local nondestructive measurements of the ferrite film parameters such as ferromagnetic resonance linewidth ΔH , saturation magnetization M_s , and thickness L in an area of the film with 1 mm diameter. Thus, the YIG film waveguide with following parameters was chosen: $\Delta H = 0.5$ Oe at 5 GHz, $4\pi M_s = 1760$ G, and $L = 9.1$ µm.

Distribution of the electric field and permittivity. The spatial distribution of the electric field in the longitudinal section of the BST slab shown in Fig. 1a was calculated by the finite element method with the FlexPDE software (www.pdesolutions.com). It was assumed that the distribution of charges and fields inside the ferroelectric obey the two-dimensional Poisson equation. The Poisson equation additionally took into account the dependence of the dielectric

constant of the ferroelectric slab on the electric field. The distribution of dielectric permittivity ϵ of the BST slab shown in Fig. 1c was calculated with the use of the electric field distribution shown in Fig. 1a and Eq. (1).

Data availability

The data that support the findings of this study are available from the corresponding author upon request.

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Author contributions

A.B.U. proposed the original concept of the DEMC. A.A.N. developed the theory. A.B.U., A.V.D., D.A.B. A.A.Serha and B.A.K. planned the experiment. A.V.D. and D.A.B. took the measurements. A.B.U., A.A.N., and B.A.K. fabricated and characterized YIG films. A. A.Semenov and A.A.N. fabricated and characterized BST slabs. A.V.D. and A.A.N. performed numerical simulations. All authors analyzed the data and participated in the preparation of the paper. B.H., E.L., and B.A.K. supervised the project.

Competing interests

The authors declare no competing interests.

Additional information

Correspondence and requests for materials should be addressed to A.B.U.

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