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An Ultra-Sub-Wavelength Microwave Polarization Switch Implemented with Directed Surface Acoustic Waves in a Magnonic Crystal

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The ability to switch the polarization of a transmitted electromagnetic wave from vertical to horizontal, or vice versa, is of great technological interest because of its many applications in long distance communication. Binary bits can be encoded in two orthogonal polarizations and transmitted securely from point to point. Polarization switches, however, are usually much larger than the wavelength of the electromagnetic wave. Consequently, most research in this area has focused on the optical regime where the wavelength is relatively short (~1 μ m), so that the switch being much larger than the wavelength is not too inconvenient. However, this changes in the microwave regime where the wavelength is much larger (typically > 1 cm). That makes a microwave ultra-sub-wavelength polarization switch very attractive. Here, we report such a switch made of an array of magnetostrictive nanomagnets (~100 nm lateral dimension) deposited on a piezoelectric substrate to make an "artificial magnonic crystal". A surface acoustic wave (SAW) launched in the substrate with suitable electrodes excites spin waves in the nanomagnets via phonon-magnon coupling, resulting in radiation of electromagnetic waves via magnon-photon coupling. The polarization of the beam radiated in *one particular direction* at a given frequency can be rotated through \sim 90° by switching the direction of SAW propagation in the piezoelectric substrate between two mutually orthogonal directions. By aligning the transmitter and the receiver along that particular direction (known only to authorized users), one can communicate securely from point to point, without the need for encryption or cryptography.

KEYWORDS

polarization switch, ultra-sub-wavelength magneto-elastic antenna, magnonic crystal, surface acoustic wave

1 | INTRODUCTION

In quantum communication, information is encoded in the polarization of a photon for quantum key distribution and other tasks that call for an unconditionally secure link. In classical communication, encoding information in the polarization of an electromagnetic wave offers some advantages as well, such as polarization encoded secret sharing [1, 2] and multiple data streams sent on the same frequency channel using different polarization states to save bandwidth. The latter is known as *polarization division multiplexing* which is used in satellite communication but could be also used in on-chip communication to reduce both bandwidth and component count.

For digital data transmission via two orthogonal polarizations encoding bits 0 and 1, one would require a polarization switch that will switch the polarization of an electromagnetic wave from approximately horizontal (encoding the bit 0) to approximately vertical (encoding the bit 1), or vice versa. Polarization purity is not a concern for such applications. As long as the two polarizations are distinguishable (i.e., approximately orthogonal), it will suffice. Most polarization switches work at optical frequencies and are implemented with various techniques such as rotating waveplates [3], Babinet-Soleil compensators [4], Berek rotary compensators [5], fiber coil polarization controllers [6], Faraday rotators [7], degree of polarization generators [8], lithium niobate electro-optics [9], liquid crystals [10], digital micromirrors [11], graphene metasurfaces [12] and on-chip photonic circuits [13, 14, 15].

All of the above constructions are typically much larger than the wavelength. While this is less of a problem in the domain of optics where the wavelength is usually $1 - 10 \mu$ m, it is a serious problem in the microwave frequency region where the wavelength can be several cm. Therefore, sub-wavelength polarization switches are very attractive for the microwave regime. Here, we demonstrate a microwave polarization switch (working at 1-30 GHz) that is orders of magnitude *smaller* than the wavelength. This can have applications in ultra-compact polarization division multiplexers and digital data transmitters in the microwave range.

2 | RESULTS AND DISCUSSION

The structure of the polarization switch is shown in Fig. 1. It consists of a periodic two-dimensional array of magnetostrictive nanomagnets (made of cobalt) deposited on a piezoelectric substrate ($LiNbO_3$). This is a periodic system for a spin wave (magnons) in the nanomagnets and hence it is called an "artificial magnonic crystal". It is the same system that was used in ref. [17] for beam steering. Here, it is used for a different purpose, namely polarization switching. All



FIGURE 1 Schematic of the polarization switch. A two-dimensional periodic array of magnetostrictive nanomagnets is delineated on a piezoelectric substrate. The different pairs of electrodes, such as (3,4) or (5,6) can be connected to a microwave voltage source to launch surface acoustic waves (SAWs) in different directions. The polarization of the radiated electromagnetic beam in any given direction at any given microwave frequency depends on the direction of SAW propagation. Thus, by switching the electrode pairs, one can switch the polarization. Reproduced from [16] with the permission of IEEE.

antenna properties such as the scattering parameter S_{11} spectrum, radiation efficiencies at different frequencies, etc. can be found in refs. [16, 17].

The LiNbO₃ substrate is 0.5 mm thick. The nanomagnets are slightly elliptical with major axis ~110 nm and minor axis ~100 nm. The thickness is ~ 6 nm. Each nanomagnet has a 5 nm thick Ti layer underneath for adhesion to the substrate. The nanomagnet array covers an area of ~100 μ m × 100 μ m and is fabricated with electron-beamlithography using a Raith Voyager e-beam writer. The substrate is spin-coated with a single layer of PMMA resist spun at 2500 rpm and baked at 110°C for 2 minutes. It is then patterned with e-beam, and developed in a methyl isobutyl ketone and isopropyl alcohol (MIBK-IPA, 1:3) solution for 60 seconds, followed by a cold IPA rinse. After the patterning is complete, a 5 nm-thick titanium (Ti) adhesion layer is deposited using electron beam evaporation at a base pressure of 2.3 × 10⁻⁷ Torr, followed by the deposition of 6 nm thick cobalt. Lift-off is performed using remover PG solution. A scanning electron micrograph of the nanomagnets can be found in ref. [16]. The electrodes for launching surface acoustic waves are delineated with optical lithography.

A surface acoustic wave (SAW) is launched in two mutually orthogonal directions by activating electrode pairs (3,4) or (5,6) (see Fig. 1). The SAW excites spin waves in the magnonic crystal via phonon-magnon coupling, which radiate electromagnetic waves via magnon-photon coupling [16, 17, 18]. Unlike a conventional electromagnetic antenna that radiates electromagnetic waves owing to fluctuating charges or time-varying electric dipoles, these structures (nano-antennas) radiate electromagnetic waves due to fluctuating magnetization associated with spin waves [16, 17, 18, 19, 20, 21]. Hence, they do not behave as traditional antennas and are not constrained by the Harrington limit or Chu's limit that afflict the gain and bandwidth of traditional antennas.

In the past, we measured the radiation pattern of these samples by propagating a SAW in two different directions [16]. We can apply a microwave frequency voltage between either electrode pairs (3,4) or (5,6) to launch SAWs in two mutually perpendicular directions. We then measure the radiation patterns in an anechoic chamber for these two different directions of SAW propagation. The patterns are measured in the plane of the nanomagnets and in the two planes transverse to the plane of the nanomagnets. The in-plane results are shown in Fig. 2 for both horizontal and vertical polarizations of the emitted radiation. The radiation patterns were measured in an AMS-8701 Anechoic Chamber, Antenna Measurement System using a 3164-10 Open Boundary Quad-ridged Horn Antenna.



FIGURE 2 Radiation patterns (gain in db) in the *plane of the nanomagnets* at different SAW excitation frequencies when the microwave source to launch the SAW is connected between two different electrode pairs in order to make the SAW propagate along two different directions. (a) "orientation 1" is defined as the case when the microwave source is connected between electrodes 3 and 4 to launch a SAW propagating parallel to the major axes of the elliptical nanomagnets, while "orientation 2" refers to the case when the microwave source is connected between electrodes 5 and 6 to launch a SAW propagating parallel to the elliptical nanomagnets (b) Definition of the "directions" for the radiation pattern; 0° is along the minor axes and 90° is along the major axes of the nanomagnets. (c) Radiation patterns for horizontal polarization for both "orientations". (d) Radiation patterns for vertical polarization for both "orientations". Note that the radiation pattern is "orientation"-dependent, meaning that it depends on the direction of SAW propagation. Reproduced from [16] with permission of the IEEE.



FIGURE 3 Radiation patterns for horizontal and vertical polarizations (gain in absolute units, as opposed to dbi) in the *plane of the nanomagnets* at different SAW excitation frequencies when the microwave source to launch the SAW is connected between two different electrode pairs in order to make the SAW propagate along two different directions designated as "orientation 1" and "orientation 2".

Fig. 2 shows that there is significant anisotropy in the radiation pattern at all frequencies measured (despite this being an ultra-sub-wavelength structure that should behave like a point source), but more importantly, the radiation pattern depends on the direction of SAW propagation (the difference between "orientation 1" and "orientation 2"). The difference is, of course, more pronounced at certain frequencies.

We investigated the directional dependence via micromagnetic simulations. Theoretical simulations revealed that the nature of the spin waves excited in the nanomagnets is strongly influenced by whether the surface acoustic wave propagates parallel to the major axis of the elliptical nanomagnets (as would be the case if electrodes 3 and 4 in Fig. 1 were excited) or parallel to the minor axis of the nanomagnets (as would be the case if electrodes 5 and 6 were excited instead; see supplementary material of [17]). As a result, the electromagnetic radiation pattern also depends

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FIGURE 4 Radial plot (in radians) of the polarization angle θ in the plane of the nanomagnets at different frequencies for two mutually perpendicular directions of SAW propagation labeled as "orientation 1" and "orientation 2". The far right panel shows that if we place the detector at 75° angle in the plane of the nanomagnets, then at 5.9 GHz frequency, we will receive and detect two mutually orthogonal polarizations if we switch the direction of SAW propagation from "orientation 1" to "orientation 2" by switching the electrode pairs used to launch the SAW.

strongly on the direction of SAW propagation [16].

Why the spin wave pattern depends on the direction of SAW propagation is easily understood. The surface acoustic wave subjects the nanomagnets to periodic strain. Strain acts like an effective magnetic field in a magnetostrictive nanomagnet and in the case of SAW, an effective periodic magnetic field will appear in the nanomagnet [22]. This periodic field will make the magnetization process and oscillate in time, thereby producing a spin wave. The direction of the effective magnetic field is roughly along the direction of SAW propagation [22]. Therefore, if we change the direction of SAW propagation, we will change the direction of the effective time-varying magnetic field in the nanomagnet and this will change the axis of precession of the magnetization within the nanomagnet, resulting in a change in the oscillations (both amplitude and phase) of the x-, y- and z-components of the magnetization, i.e. the spin wave pattern will change [17]. Ref. [17] found that this changed the radiation *spectrum*, whereas ref.[16] showed that this also changes the radiation *pattern* for either horizontal or vertical polarization.

Since the spin waves radiate the electromagnetic waves, changing the spin wave patterns in space by changing the direction of SAW propagation also *changes the polarization of the radiated beam in any direction*. This polarization change was not studied earlier and here we report that study. The Supporting Information provides a phenomenological theory of why the polarization will change if we change the direction of SAW propagation.

2.1 | Polarization dependence on the direction of SAW propagation

In Fig. 3, we first plot the radiation patterns in the plane of the nanomagnets for both vertical and horizontal polarizations in absolute units (as opposed to in db) for both directions of SAW propagation. This is done for different frequencies.

Let us say that at a given frequency the horizontal polarization value in a given direction at a given frequency is h and the vertical polarization value is v. We define a polarization angle θ as

$$\theta = tan^{-1} \left(\frac{v}{h}\right).$$

In this case, $\theta = 0$ corresponds to horizontal polarization and $\theta = \pi/2$ radians corresponds to vertical polarization.

In Fig. 4, we show the radial plot of θ at different frequencies in radians. Note that at 5.9 GHz, in the 75° direction, $\theta \approx 1.5$ radians for orientation 2 and ≈ 0.1 radians for orientation 1. Hence, the beam is 99.5% horizontally polarized for orientation 1 and 99.5% vertically polarized for orientation 2. Thus, by switching the direction of SAW propagation from orientation 1 to orientation 2, we can change the polarization of the beam radiated in the 75° direction at 5.9 GHz (in the nanomagnets' plane) from nearly *horizontal* to nearly *vertical* with very high degree of polarization purity, more than enough purity for binary encoding of data. We can place the receiver at 75° angle as shown in the right panel of Fig. 4 and receive either horizontal polarization or vertical polarization by switching the direction of SAW propagation by switching the electrode pairs that are activated to launch the SAW. This is the basis of the polarization switch. Note that the positions of the transmitting device and the receiver do not have to be fixed, but their relative alignment have to be fixed in this scheme. This enables *point-to-point* communication via polarization.

2.2 | Security of communication

The fact that the point-to-point communication via polarization encoding works only for *a specific alignment of the transmitter and receiver* adds an additional layer of security. The authorized sender has access to the polarization radial plot and can inform the authorized receiver where to place the receiving device. An unauthorized receiver, intent on intercepting the message (eavesdropping), will not know where to place the receiver and will place it at a wrong location with very high probability. The eavesdropper will therefore not receive binary polarization states and hence cannot eavesdrop or intercept the message. For example, if the eavesdropper places the receiver at 0° angle, then for orientation 1, $\theta \approx 0$ radians which means that the beam is horizontally polarized and for orientation 2, θ is again 0 radians and the beam is again horizontally polarized. If horizontal polarization encodes the bit 0, then the eavesdropper will constantly received a string of 0-s and no real message. Similarly, if the eavesdropper places the receiver at 180° angle, $\theta = 0.7$ radians for orientation 1 and 1.3 radians for orientation 2. In this case, the received beam will be 58% horizontally polarized for orientation 2. The poor polarization purity precludes deciphering the binary bits and hence the message. Thus, without precise knowledge of the correct location for the receiver, eavesdropping is impossible and confidentiality is assured. This eliminates the need for encrypting the message or resorting to cryptography, which are always vulnerable to sophisticated attacks.

The scheme is also unclonable since the specific alignment that works will vary from sample to sample because of unavoidable manufacturing variations. Thus, the specific alignment is a "fingerprint" of any chosen antenna and hence can act as a physically unclonable function (PUF) that cannot be reproduced or predicted, thereby providing strong security.

3 | CONCLUSION

We have presented a novel polarization switch for microwave signals that is nearly three orders of magnitude *smaller* than the wavelength. This can be used as an ultra-compact polarization division multiplexer and to transmit digital data encoded in two mutually orthogonal polarizations at microwave frequencies for point-to-point communication. A phenomenological theory of why the polarization of the emitted electromagnetic radiation will change upon changing the direction of surface acoustic wave propagation in the device is presented as Supporting Information.

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Supporting Information

Supporting information can be found at the Wiley Online Library or from the corresponding author.

Conflict of Interest

The authors declare no conflict of interest.

Data Availability Statement

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

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