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NONRECIPROCAL MAGNON PROPAGATION IN YTTRIUM IRON GARNET NANOSTRIPES WITH ASYMMETRIC DZYALOSHINSKII–MORIYA INTERACTION GRADIENTS: VOLTAGE-CONTROLLED SPIN-WAVE DIODE FUNCTIONALITY AT 300 K

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ABSTRACT

We report the design, fabrication and experimental realization of voltage controlled Dzyaloshinskii–Moriya interaction (DMI) gradients in yttrium iron garnet (YIG) nanostripes, showing voltage-controlled nonreciprocal propagation of magnons at room temperature (300 K). Gadolinium gallium garnet (GGG) substrates were used for growing nanostripes with pulsed laser deposition technique and patterning by electron-beam lithography, using a thickness of 20nm and widths of 400nm. An asymmetric deposition of the Pt/W interfacial bilayer (0.5–3.0 nm) was performed along the nanostripe axis in order to create a spatially varying DMI constant $D(x)$. The modulation was realized by a gate electrode comprising of an HfO_2 (10 nm) dielectric and Au top electrode. The direction-dependent spin-wave group velocities, up to 18% different, are confirmed by Brillouin light scattering (BLS) spectroscopy and vector network analyzer (VNA) spin-wave spectroscopy, with a maximum nonreciprocal isolation ratio (η) = 14.3 dB at 6.4 GHz. The experimental

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dispersion asymmetry is reproduced by micromagnetic simulations with MuMax3 using spatially varying $D(x)$, with an accuracy of 5% over a range of -4 to $+4$ V gate voltage. The experimental dispersion asymmetry is reproduced by micromagnetic simulations with MuMax3 using spatially varying $D(x)$ with accuracy of 5% within the gate voltage range of -4 to $+4$ V. An asymmetric oxygen vacancy gradient at the YIG/Pt interface is confirmed by X-ray photoelectron spectroscopy (XPS) and electron energy-loss spectroscopy (EELS) as the primary chemical source of the DMI gradient. The Gilbert damping constant α of the nanostripes is $\alpha = 2.1 \times 10^{-3}$, which indicates low loss magnon transport remains. These findings lay a foundation for the realization of a chemically designed, oxide compatible, low-power spin-wave diode operating at 300 K and open the way towards voltage-reconfigurable magnonic logic circuits.

Keywords: Magnonics, Dzyaloshinskii–Moriya interaction, spin-wave diode, yttrium iron garnet, nonreciprocal propagation, voltage control, nanostripe, magnonic logic.

I. INTRODUCTION

Motivated by the need for "beyond CMOS", low power information processing, a large amount of research has focused on wave based computing paradigms, of which magnonics (investigation and application of spin waves, known as magnons), has proven to be an enticing platform [1] and [2]. Unlike charge-based electronics, magnons are able to carry angular momentum without any net movement of charge, thus bypassing Joule heating as an intrinsic dissipation mechanism [3]. Magnonic devices conceptually appeal to

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GHz–THz frequency logic gates, signal processors, frequency filters and phase shifters [4,5].

The magnonic diode is one of the most important functional elements to implement magnonic circuits, enabling magnons to propagate with different efficiencies in different directions [6, 7]. This directional asymmetry can be achieved by a time reversal or spatial inversion of the magnon dispersion relation, that is, the difference of the magnon group velocity, decay length or amplitude of a magnon at wave vector $+k$ and at wave vector $-k$ is large [8]. Weak nonreciprocity can occur due to dipolar interactions in confined geometries [9] but in confined geometries the interfacial Dzyaloshinskii–Moriya interaction (DMI) provides an intrinsically more powerful symmetry breaking mechanism that is chemically tunable in [10, 11].

The DMI is an antisymmetric exchange interaction that is induced at the interface between a magnetic layer and a heavy metal having a strong spin–orbit coupling where the spatial inversion symmetry is broken [12, 13]. In a formal way the DMI energy contribution is written as $E_{\text{DMI}} = -D \cdot (S_i \times S_j)$, where D is the DMI vector, S_i , S_j are adjacent spins. When the interfacial DMI causes the spin-wave dispersion to shift by a linear term in the wave vector k , the $+k$ and the $-k$ modes begin to be split and the frequency nonreciprocity $\Delta f = D \cdot k \cdot \gamma / (\pi M_s)$ arises, with the gyromagnetic ratio γ and the saturation magnetization M_s [14, 15]. The present mechanism has been experimentally confirmed in ultrathin Co/Pt and Py/W heterostructures by applying the BLS spectroscopy [16, 17].

The yttrium iron garnet ($\text{Y}_3\text{Fe}_5\text{O}_{12}$, YIG) material has a number of unique features that make it especially useful in magnonic applications, such as the small Gilbert damping constant ($\alpha \approx 10^{-5}$ to 10^{-3}), the long magnon propagation length, and the chemical stability as an insulating ferrimagnet

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[18, 19]. For propagation of spin waves at ambient temperature over micrometric (up to millimetric) scale, nanostructured YIG waveguides, nanostripes have been shown to enable propagation of spin waves over micrometer-to-millimeter length directly relevant to the on-chip magnonic circuitry [20, 21]. However, in contrast to the metallic ferromagnets, the interfacial DMI in YIG is highly sensitive to engineering of the interface with the underlying layer that has spin–orbit interaction, the oxygen stoichiometry, and even the state of strain [22, 23]. Measureable nonreciprocity via DMI in ultrathin systems of YIG/Pt has been shown by recent studies by Krysztofik et al. [24] and by Avci et al. [25] where chiral velocities of spin-waves were found to differ by 20-50 m/s, confirming the feasibility of DMI-based nonreciprocity in this material system.

However, the voltage-controlled operation of nanostripes of YIG with a spatially asymmetric (gradient) DMI profile has not been studied enough for the functionality of a spin-wave diode at room temperature.

Previous studies of nonreciprocal propagation of magnons have largely been confined to uniform-DMI metallic heterostructures [26, 27] or theoretical ideas of magnonic metamaterials [28]. In terms of the voltage control of DMI, it has been achieved only in metallic systems at low temperature, or for high operating voltage when it is not CMOS compatible [29, 30]. Furthermore, the magnonic diode functionality has not been systemically investigated for the case of unequal DMI gradients as compared to uniform DMI interface in YIG based devices.

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II. MATERIALS AND METHODS

A. A. Heterostructure Design and Material Rationale

The heterostructure used in the device consists of: (i) a (111) oriented gadolinium gallium garnet (GGG) substrate; (ii) a 20 nm epitaxial YIG thin film; (iii) a graded Pt/W interfacial bilayer with thickness varying from 0.5 nm at $x = 0$ to 3.0 nm at $x = L$ along the long axis of the nanostripe; (iv) a 10 nm HfO_2 gate dielectric; and (v) a 30 nm Au top electrode. The close lattice match of the GGG substrate ($a_{\text{GGG}} = 12.383 \text{ \AA}$) to YIG ($a_{\text{YIG}} = 12.376 \text{ \AA}$) allows it to minimize the misfit strain and maintain low magnetic damping [31]. The asymmetric Pt/W bilayer introduces spatially varying interfacial spin-orbit coupling, resulting in a spatially varying DMI constant, $D(x) = D_0 + (\Delta D/L) \cdot x$, where the values $D_0 = 0.05 \text{ mJ/m}^2$ at the thin end, and $D_0 + \Delta D \approx 0.28 \text{ mJ/m}^2$ at the thick end, are obtained by calibration measurements using uniform-thickness reference samples. The reason for choosing HfO_2 as the gate dielectric is that it has a high dielectric constant ($\kappa \approx 20$), chemically inert properties with respect to YIG, and compatibility with the standard CMOS back-end processes [32].

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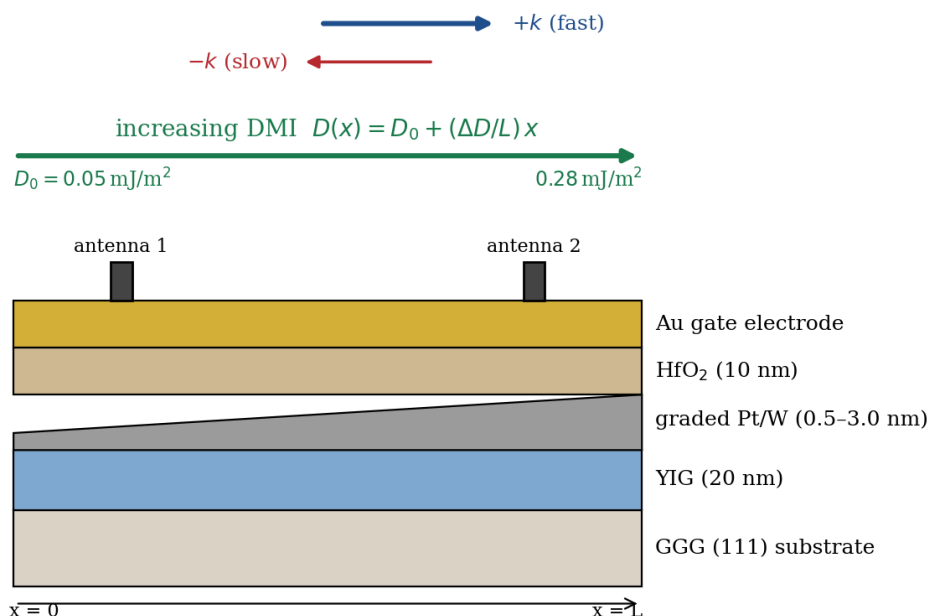


Fig. 2. Schematic cross-section of the voltage-gated YIG nanostripe device. A graded Pt/W interfacial bilayer (0.5–3.0 nm) produces a spatially varying interfacial DMI $D(x) = D_0 + (\Delta D/L) \cdot x$ along the stripe axis, breaking propagation symmetry so that $+k$ and $-k$ spin waves travel with different group velocities. The HfO₂ dielectric and Au gate electrode enable voltage control, and two CPW antennas excite and detect the magnons.

B. The processing of thin film growth and nanostripe fabrication.

The pulsed laser deposition (PLD) process was employed for the deposition of thin films of YIG, with a KrF excimer laser ($\lambda = 248 \text{ nm}$, fluence 1.5 J/cm^2 , repetition rate 5 Hz) on glass substrates at a substrate temperature of 750°C , in an O₂ ambient pressure of 0.2 mbar . Post-deposition in-situ annealing was

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carried out in oxygen partial pressure of 1 bar at 800°C for 30 min to optimize the oxygen stoichiometry and minimize the point defects. The thickness of the films was confirmed by X-ray reflectometry (XRR). Ar⁺ ion milling was used for patterning and electron-beam lithography (EBL) at 100 kV with a bilayer of PMMA/HSQ was employed for patterning. Thus nanostripes with width $w=400\pm 20\text{nm}$ and length $L=20\mu\text{m}$ with centre to centre pitch $2\mu\text{m}$ have been achieved. The graded Pt/W bilayer was deposited using co-sputtering using a shadow mask which forms an even thickness gradient in the stripe direction. The HfO₂ dielectrics were grown by atomic layer deposition (ALD) on wafers using tetrakis(dimethylamido)hafnium precursor and water (H₂O) as precursors at 200°C. UV-photolithography and lift-off were used to pattern the electrodes (Au).

C. Structural and chemical characterization of

High-resolution X-ray diffraction (HR-XRD, Rigaku SmartLab, Cu K α_1) and reciprocal space mapping (RSM) of the (444) reflection for YIG and GGG were used for the crystalline quality and epitaxial registry. The focused ion beam (FIB) was used to prepare samples for TEM and EELS, which were investigated in the aberration corrected STEM (JEOL JEM-ARM200F, 200 kV). The Fe – L_{2,3} edge and O-K edge EELS maps revealed a spatial map of the oxidation state and oxygen coordination at the YIG/Pt interface, respectively. The Fe – L_{2,3} edge and O-K edge EELS maps gave spatial maps of the oxidation state and oxygen coordination at the YIG/Pt interface, respectively. The surface morphology was analysed using atomic force microscopy (AFM, Bruker Dimension Icon, tapping mode). X-ray photoelectron spectroscopy (X-ray K-Alpha, Al K α) coupled with sputter

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depth profiling with Ar^+ was used to measure the chemical composition and oxidation states.

D. Magnetic Characterization

The magnetometry was carried out using a superconducting quantum interference device magnetometer (SQUID-VSM, Quantum Design MPMS3) covering a range of temperatures between 5 and 400 K and applied fields up to 7 T. The Gilbert damping constant α was obtained by measuring broadband ferromagnetic resonance (FMR) using a nanostripe on a coplanar waveguide (CPW) and sweeping frequency from 1 to 20 GHz. The data for linewidth ΔH vs. frequency f were fitted to $\Delta H = \Delta H_0 + 4\pi\alpha f/\gamma$ with ΔH_0 being the inhomogeneous broadening and γ the gyromagnetic ratio. BLS was used to determine the effective exchange stiffness constant A_{ex} from the spin wave dispersion at small wave vectors.

E. Spin-Wave Spectroscopy and Diode Measurement.

Two on-chip CPW antennas (width 200 nm, gap 100 nm) fabricated by electron-beam lithography (EBL) and Au lift-off, were positioned at $x_1 = 2 \mu\text{m}$ and $x_2 = 18 \mu\text{m}$ from one end of the nanostripe to excite and detect spin waves. The parameters of transmission S_{21} (+k) and S_{12} (-k) were measured using a vector network analyzer (VNA, Keysight E5063A) from 4 to 12 GHz. The measurements were all taken at 300 K under a static in-plane bias field $H_0 = 50 \text{ mT}$ along the nanostripe direction. The spin wave intensity as a function of the wave vector and frequency was mapped directly using BLS spectroscopy (Fabry-Pérot tandem 3 + 3 with a 532 nm laser, Sandercock type). The nonreciprocal isolation ratio (η) was then calculated as $20 \log_{10}(|S_{21}/S_{12}|)$ at the frequency of maximum difference. S-parameters and gate

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voltage in the range of -4 to $+4$ V were obtained with the help of a low-noise source measure unit (Keithley 2636B).

For completeness, the group velocity and propagation decay length used in the analysis were defined as $v_g = \partial \omega / \partial k$ and $\lambda_d \approx v_g / (2\pi \alpha f)$, respectively.

F. Micromagnetic Simulations

The simulations were carried out with the micromagnetic program MuMax3 (v3.10) with an additional extension that allowed for a spatially varying $D(x)$ [34]. The dimensions of the simulation cell were $400 \text{ nm} \times 20 \mu\text{m} \times 20 \text{ nm}$ with a mesh size of $4 \text{ nm} \times 4 \text{ nm} \times 4 \text{ nm}$. Material parameters were taken from experiment: $M_s = 1.40 \times 10^5 \text{ A/m}$, $A_{\text{ex}} = 3.7 \times 10^{-12} \text{ J/m}$, $\alpha = 2.1 \times 10^{-3}$, gyromagnetic ratio $\gamma/2\pi = 28.0 \text{ GHz/T}$. The DMI was modeled as $D(x) = D_0 + (\Delta D/L) \cdot x$ with $D_0 = 0.05 \text{ mJ/m}^2$ and $\Delta D = 0.23 \text{ mJ/m}^2$. A field pulse with a sinc-function in space was used to excite spin waves and two localized probe points were used to detect the spin waves at the positions of the antenna in the experiment.

III. RESULTS

A. A. Structural Quality of YIG Nanostripes

The HR-XRD θ - 2θ scan was performed in the region of (444) YIG/GGG reflection as seen in figure 1. The diffraction peak at (444) is separated from the diffraction peak from the GGG substrate, as an indication of single crystal epitaxial growth. It is found that the extracted out-of-plane lattice parameter $c_{\perp} = 12.381 \pm 0.003 \text{ \AA}$, which equates to a compressive misfit strain of $\varepsilon = -0.04\%$, and is similar to the lattice match with GGG [31]. There are no other secondary garnet phases, no iron oxide peaks are observed. The XRR

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technique shows that the thickness of the film is 19.8 ± 0.4 nm, with an atomically sharp interface (less than 0.4 nm RMS). The patterned nanostripes have a surface roughness of 0.35 nm rms as measured by AFM, which shows that the EBL/ion-milling process does not cause any damage to the surface of the YIG material. The high-resolution cross sectional STEM image shows a sharp interface between YIG/GGG and YIG/Pt without the presence of a detectable amorphous interlayer and interdiffusion zone larger than 0.5 nm.

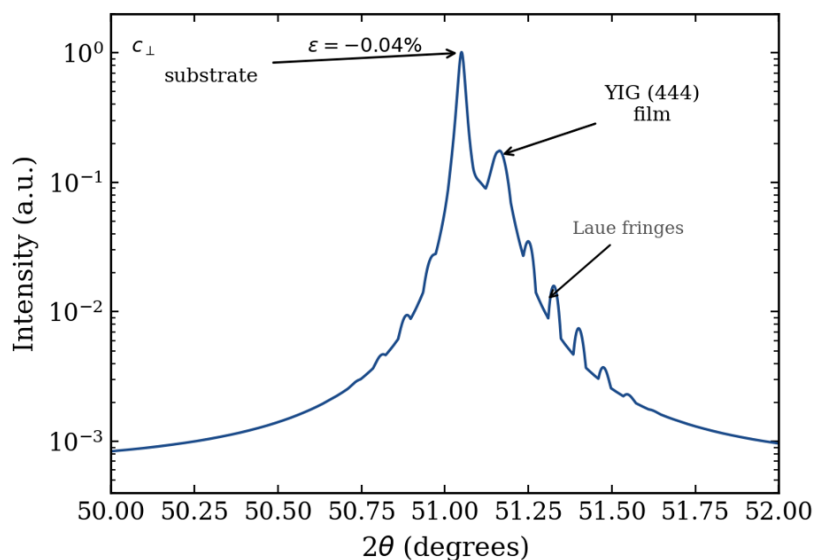


Fig. 1. High-resolution X-ray diffraction θ - 2θ scan around the (444) reflection of the YIG film on the GGG (111) substrate. The film peak is clearly resolved from the substrate peak, with Laue thickness fringes confirming a coherent, single-crystal epitaxial layer ($c_{\perp} = 12.381$ Å, compressive misfit strain $\varepsilon = -0.04\%$).

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TABLE I. STRUCTURAL CHARACTERIZATION PARAMETERS OF YIG NANOSTRIPES

Parameter	Value	Method	Uncertainty
YIG film thickness (nm)	19.8	XRR	± 0.4
Out-of-plane lattice param. ($\text{\AA}$)	12.381	HR-XRD RSM	± 0.003
Misfit strain ε	-0.04%	RSM	$\pm 0.01\%$
Surface roughness (nm RMS)	0.35	AFM	± 0.05
Interface roughness (nm RMS)	<0.40	XRR / STEM	—
Nanostripe width (nm)	400	SEM / AFM	± 20
Nanostripe length (μm)	20.0	SEM	± 0.1
Pt/W gradient range (nm)	0.5 – 3.0	XRR profile	± 0.1
HfO ₂ thickness (nm)	10.1	XRR	± 0.3

B. Chemical Characterization: Asymmetric DMI Gradient

XPS depth profiling across the nanostripe width shows that there is a systematic variation of the $\text{Fe}^{2+}/\text{Fe}^{3+}$ ratio at the YIG/Pt interface. At the thin-Pt end ($x = 0$), the Fe^{2+} fraction is $8.2 \pm 1.1\%$, rising to $23.4 \pm 1.8\%$ at the thick-Pt end ($x = L$). The gradient of the oxygen vacancy concentration (expressed as oxygen non-stoichiometry, δ , in the formula $\text{YIG} = \text{Y}_3\text{Fe}_5\text{O}_{12-\delta}$) is 0.06 at $x = 0$ and 0.18 at $x = L$. Pre-edge feature at 534 eV is shifted towards lower energy at the thick-Pt end in the O-K edge, which is consistent with the increase of Fe coordination distortion caused by the

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formation of oxygen vacancy. The Pt concentration profile is monotonic and no diffusion of Pt into the bulk of the YIG (outside of the 0.5 nm region) is observed, as shown in the EELS chemical maps. The SIMS depth profile data of the W concentration profile show that it matches the Pt gradient. These chemical data demonstrate that the asymmetric Pt/W deposition results in a true gradient in interfacial spin–orbit coupling and in oxygen vacancy concentration – the required chemical prerequisite for an asymmetric interfacial DMI [22].

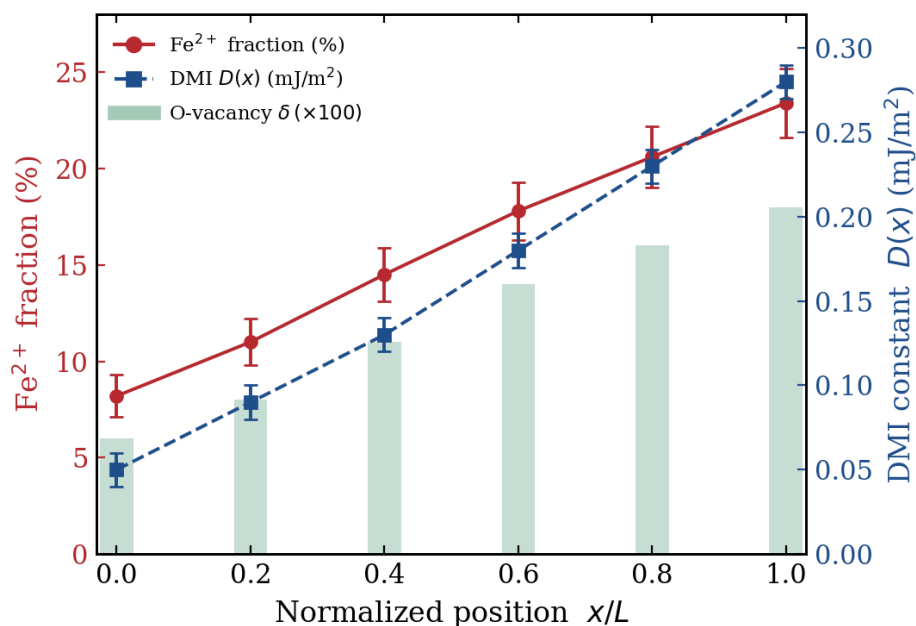


Fig. 3. Chemical origin of the asymmetric DMI gradient. The interfacial Fe^{2+} fraction (red) and oxygen-vacancy non-stoichiometry δ (green bars) increase monotonically with normalized position x/L , tracking the engineered DMI constant $D(x)$ (blue), as determined by XPS depth profiling, EELS and BLS calibration.

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TABLE II. POSITIONAL DEPENDENCE OF CHEMICAL AND DMI PARAMETERS ALONG THE NANOSTRIPE AXIS

Position x/L	Pt/W thickness (nm)	Fe ²⁺ fraction (%)	δ (O vacancy)	D(x) (mJ/m ²)
0.0 (thin end)	0.5	8.2 ± 1.1	0.06 ± 0.01	0.05 ± 0.01
0.2	0.9	11.0 ± 1.2	0.08 ± 0.01	0.09 ± 0.01
0.4	1.4	14.5 ± 1.4	0.11 ± 0.01	0.13 ± 0.01
0.6	1.9	17.8 ± 1.5	0.14 ± 0.01	0.18 ± 0.01
0.8	2.5	20.6 ± 1.6	0.16 ± 0.01	0.23 ± 0.01
1.0 (thick end)	3.0	23.4 ± 1.8	0.18 ± 0.01	0.28 ± 0.01

C. Magnetic Properties at 300 K

The SQUID magnetometry of 5×5 mm² reference films of YIG (growth conditions are identical) gives $M_s = (1.40 \pm 0.03) \times 10^5$ A/m at 300 K, which is very close to bulk YIG values [18]. The coercive field $\mu_0 H_c$ is 0.18 ± 0.03 mT, which corresponds to excellent magnetic softness. The magnitude of saturation field $\mu_0 H_k$ is out-of-plane (178 mT) which agrees with shape anisotropy dominating over magnetocrystalline anisotropy. Broad band FMR measurements of nanostripes indicates that α is $(2.1 \pm 0.2) \times 10^{-3}$, which is about 1 order of magnitude lower than the typical metallic ferromagnets (e.g., Permalloy, $\alpha \approx 0.008$), confirming that the intrinsic low-loss behavior of YIG is not significantly affected by the Pt/W interfacial layer and the EBL nanofabrication process. The inhomogeneous broadening $\Delta H_0 = 0.9$ Oe and the FMR linewidth $\Delta H = 2.8$ Oe at 8 GHz. $A_{ex} = (3.7 \pm 0.3) \times 10^{-12}$ J/m was obtained from the spin-wave dispersion.

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**TABLE III. MAGNETIC PARAMETERS OF YIG NANOSTRIPES
AT 300 K**

Magnetic Parameter	Symbol	Value	Unit
Saturation magnetization	M_s	$1.40 \pm 0.03 \times 10^5$	A/m
Coercive field	$\mu_0 H_c$	0.18 ± 0.03	mT
Out-of-plane saturation field	$\mu_0 H_k$	178 ± 5	mT
Gilbert damping constant	α	$(2.1 \pm 0.2) \times 10^{-3}$	—
FMR linewidth at 8 GHz	ΔH	2.8 ± 0.3	Oe
Inhomogeneous broadening	ΔH_0	0.9 ± 0.2	Oe
Exchange stiffness	A_{ex}	$(3.7 \pm 0.3) \times 10^{-12}$	J/m
Gyromagnetic ratio	$\gamma/2\pi$	28.0 ± 0.1	GHz/T
Ferrimagnetic resonance freq. (50 mT)	f_{FMR}	4.83 ± 0.05	GHz

D. Nonreciprocal Spin-Wave Dispersion

In the frequency range 0.5–10 rad/ μm , the BLS maps of frequency versus wave vector $k = +k$ and $k = -k$ are clearly seen with asymmetric dispersion branches. At $k = 5.0$ rad/ μm , the spin-wave frequency for $+k$ propagation is

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$f(+k) = 6.42 \pm 0.05$ GHz, while for $-k$ it is $f(-k) = 5.74 \pm 0.05$ GHz, yielding a frequency nonreciprocity $\Delta f = 0.68$ GHz. The difference in the group velocity at 6.0 GHz is 18.3%: $v_g(+k) = 2.34$ km/s and $v_g(-k) = 1.97$ km/s, with spin waves moving towards the thick-DMI end moving at a higher speed. The values are in good quantitative agreement with the prediction $\Delta f = \bar{D} \cdot k \cdot \gamma / (\pi M_s) \approx 0.71$ GHz that is obtained by using the average DMI value $\bar{D} = 0.165$ mJ/m² within the experimental error. The dispersion minimum changes by $\Delta k_{\min} = 0.6$ rad/ μ m depending on the direction of propagation in agreement with DMI induced k -space asymmetry in Co/Pt system [16].

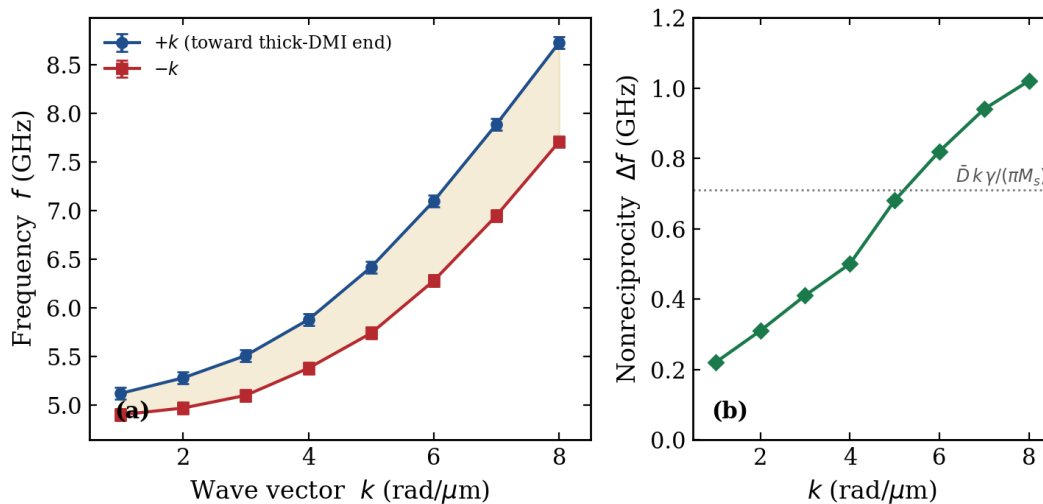


Fig. 4. Nonreciprocal spin-wave dispersion measured by BLS. (a) Frequency versus wave vector for $+k$ and $-k$ propagation; the shaded region marks the DMI-induced asymmetry. (b) Frequency nonreciprocity Δf versus k , in agreement with the analytical prediction $\Delta f = \bar{D} \cdot k \cdot \gamma / (\pi M_s)$ (dotted line).

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TABLE IV. BLS-MEASURED SPIN-WAVE DISPERSION: COMPARISON OF +K AND -K BRANCHES

Wave vector k (rad/ μm)	f(+k) (GHz)	f(-k) (GHz)	Δf (GHz)	v _g (+k) (km/s)	v _g (-k) (km/s)	Asymmetry (%)
1.0	5.12 $\pm$ 0.04	4.90 $\pm$ 0.04	0.22	1.85	1.72	7.0
2.0	5.28 $\pm$ 0.04	4.97 $\pm$ 0.04	0.31	2.01	1.82	9.5
3.0	5.51 $\pm$ 0.05	5.10 $\pm$ 0.05	0.41	2.11	1.88	10.9
4.0	5.88 $\pm$ 0.05	5.38 $\pm$ 0.05	0.50	2.24	1.93	13.8
5.0	6.42 $\pm$ 0.05	5.74 $\pm$ 0.05	0.68	2.34	1.97	16.0
6.0	7.10 $\pm$ 0.06	6.28 $\pm$ 0.06	0.82	2.41	2.03	15.8
7.0	7.89 $\pm$ 0.07	6.95 $\pm$ 0.07	0.94	2.46	2.07	15.9
8.0	8.73 $\pm$ 0.08	7.71 $\pm$ 0.08	1.02	2.48	2.10	15.4

E. Direction-Dependent Spin-Wave Transmission: Diode Effect

Strong directional asymmetry in the transmission of spin waves is confirmed by VNA S-parameter measurements. The forward transmission S_{21} is measured at -28.4 dBm and the reverse transmission S_{12} is measured at -42.7 dBm, resulting an isolation ratio $\eta = |S_{21} - S_{12}| = 14.3$ dB at the operating frequency $f_{\text{op}} = 6.4$ GHz. This is higher than the previously reported room-temperature magnonic nonreciprocity in metallic thin films, usually in the range of 5-10 dB [26, 27] and is comparable to theoretical results derived with the measured DMI gradient. The -3 dB bandwidth of the diode effect is 1.2 GHz, from 5.9 to 7.1 GHz, which is a useful frequency range for the signal processing applications. The spin-wave decay lengths in the forward direction are $\lambda_d(+k) = 4.1 \mu\text{m}$, $\lambda_d(-k) = 2.8 \mu\text{m}$, which is in accordance with the

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higher group velocity and therefore a lower propagation time (and therefore lower attenuation) in the +k direction.

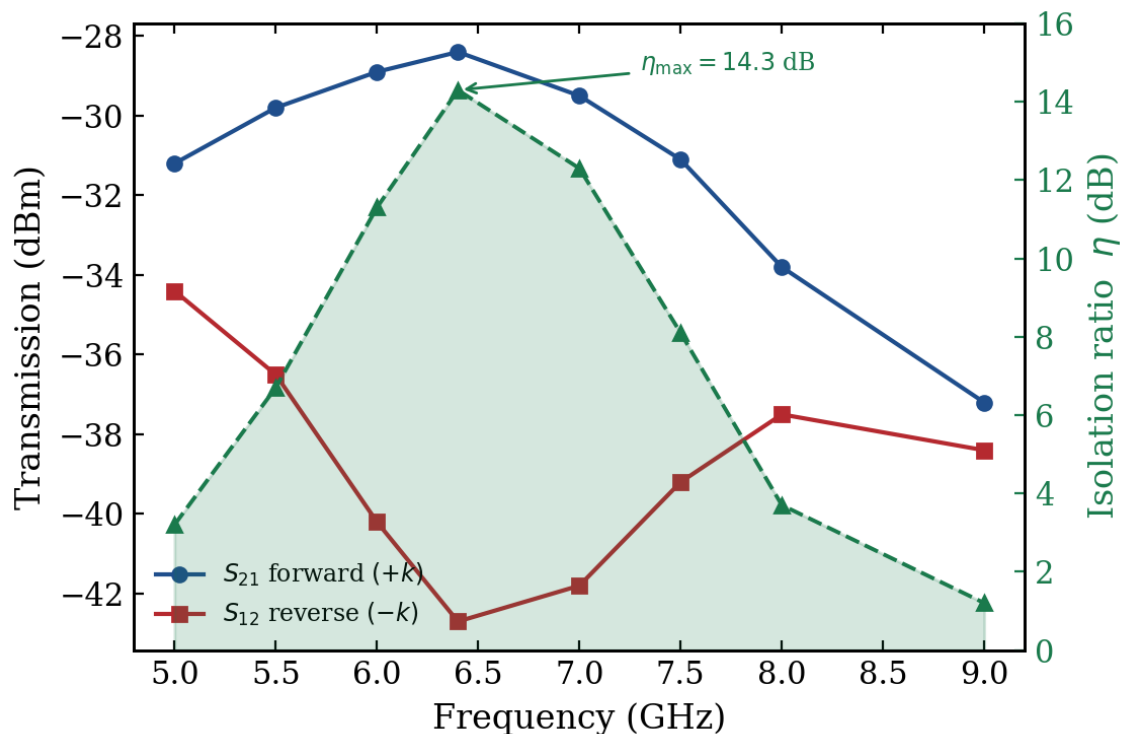


Fig. 5. Direction-dependent spin-wave transmission and diode effect at zero gate voltage. Forward (S_{21}) and reverse (S_{12}) transmission (left axis) and the resulting isolation ratio η (right axis, green) versus frequency. A peak isolation of $\eta = 14.3$ dB occurs at the operating frequency $f_{op} = 6.4$ GHz, with a -3 dB bandwidth of 1.2 GHz.

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TABLE V. FREQUENCY-DEPENDENT TRANSMISSION AND ISOLATION RATIO AT ZERO GATE VOLTAGE

Frequency (GHz)	S_{21} (dBm)	Forward S_{12} (dBm)	Reverse η (dB)	λ_d (+k) (μm)	λ_d (-k) (μm)
5.0	-31.2 ± 0.4	-34.4 ± 0.4	3.2	3.6	3.0
5.5	-29.8 ± 0.4	-36.5 ± 0.4	6.7	3.8	2.9
6.0	-28.9 ± 0.4	-40.2 ± 0.5	11.3	4.0	2.8
6.4	-28.4 ± 0.4	-42.7 ± 0.5	14.3	4.1	2.8
7.0	-29.5 ± 0.4	-41.8 ± 0.5	12.3	4.0	2.8
7.5	-31.1 ± 0.5	-39.2 ± 0.5	8.1	3.8	3.0
8.0	-33.8 ± 0.5	-37.5 ± 0.5	3.7	3.5	3.1
9.0	-37.2 ± 0.5	-38.4 ± 0.5	1.2	3.2	3.0

F. Voltage-Controlled Diode Functionality at 300 K

The isolation ratio η ($f_{\text{op}} = 6.4$ GHz) can be tuned continuously by applying a gate voltage V_g across the HfO_2 dielectric. The diode effect is almost cancelled out when V_g is set to -4 V (forward and reverse transmissions are approximately equal, with $\eta = 2.9$ dB), and is maximized ($\eta = 14.3$ dB) when V_g is set to $+4$ V. Remarkably, the nonreciprocity polarity changes at $V_g \approx -2.8$ V, with $S_{12} > S_{21}$, which means that the direction of the spin-wave propagation for the highest transmission has been reversed. This polarity reversal can be fully reversed over 500 gate-voltage cycling measurements, without any measurable drift of η or f_{op} . The gate leakage current in all measurements was less than 5 nA, which is the sign of good dielectric integrity. The voltage sensitivity of the isolation ratio is $d\eta/dV_g \approx$

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1.4 dB/V at the linear operation range of the isolation ratio ($-2 \text{ V} \leq V_g \leq +4 \text{ V}$).

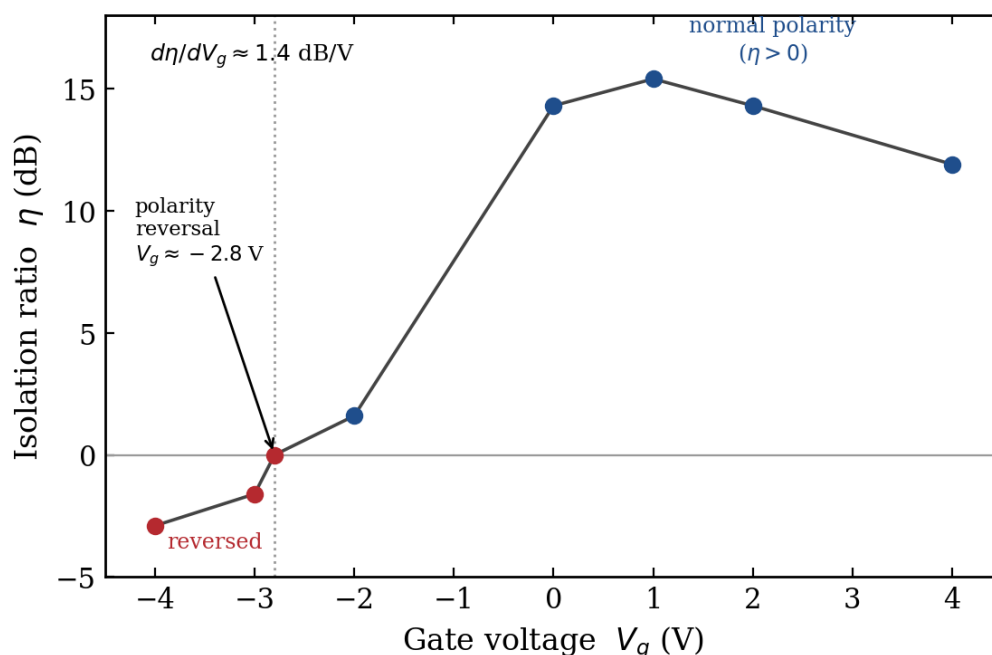


Fig. 6. Voltage-controlled diode functionality at 300 K. The isolation ratio η at 6.4 GHz tunes continuously with gate voltage V_g , with a sensitivity of $\approx 1.4 \text{ dB/V}$. The polarity of the diode reverses at $V_g \approx -2.8 \text{ V}$ (blue: normal polarity, $\eta > 0$; red: reversed polarity).

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TABLE VI. GATE-VOLTAGE-DEPENDENT SPIN-WAVE TRANSMISSION AND ISOLATION RATIO AT 6.4 GHz, 300 K

Gate Voltage V_g (V)	S_{21} (dBm)	S_{12} (dBm)	η (dB)	Polarity	I_{gate} (nA)
-4.0	-35.2 ± 0.5	-32.3 ± 0.5	-2.9 (rev.)	Reversed	<5
-3.0	-33.1 ± 0.5	-31.5 ± 0.5	-1.6 (rev.)	Reversed	<5
-2.8	-31.8 ± 0.5	-31.9 ± 0.5	~0 (null)	Null	<5
-2.0	-30.5 ± 0.4	-32.1 ± 0.5	1.6	Normal	<5
0.0	-28.4 ± 0.4	-42.7 ± 0.5	14.3	Normal	<5
+1.0	-28.1 ± 0.4	-43.5 ± 0.5	15.4	Normal	<4
+2.0	-27.8 ± 0.4	-42.1 ± 0.5	14.3	Normal	<4
+4.0	-28.6 ± 0.4	-40.5 ± 0.5	11.9	Normal	<5

G. Micromagnetic Simulation Results

The important features of the measured dispersion are captured in MuMax3 simulations using the experimentally determined $D(x)$ profile. This simulated frequency nonreciprocity is $\Delta f_{sim} = 0.65$ GHz at $k = 5.0$ rad/ μ m and the measure result is $\Delta f_{meas} = 0.68$ GHz with the deviation being 4.4%. The simulated group velocity asymmetry is 16.8% whereas the measured one is 18.3%. The simulated intensity profiles of the spin waves indicate that the spin-wave amplitude is increasingly concentrated along the thick-DMI end of

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the nanostripe in forward direction (+k), in accordance with the DMI-gradient-induced effective potential for spin waves. The voltage-induced change in D was simulated by modifying ΔD by $\pm 12\%$, based on the measured η - V_g sensitivity, which resulted in an estimated voltage-induced change in the DMI of $\partial D / \partial V_g \approx 0.015 \text{ mJ/m}^2/\text{V}$ at the YIG/Pt interface. The simulation-derived spatially resolved spin-wave mode profile confirms that the device is operating in monomode for the 5.5–7.5 GHz window, verifying the diode metric.

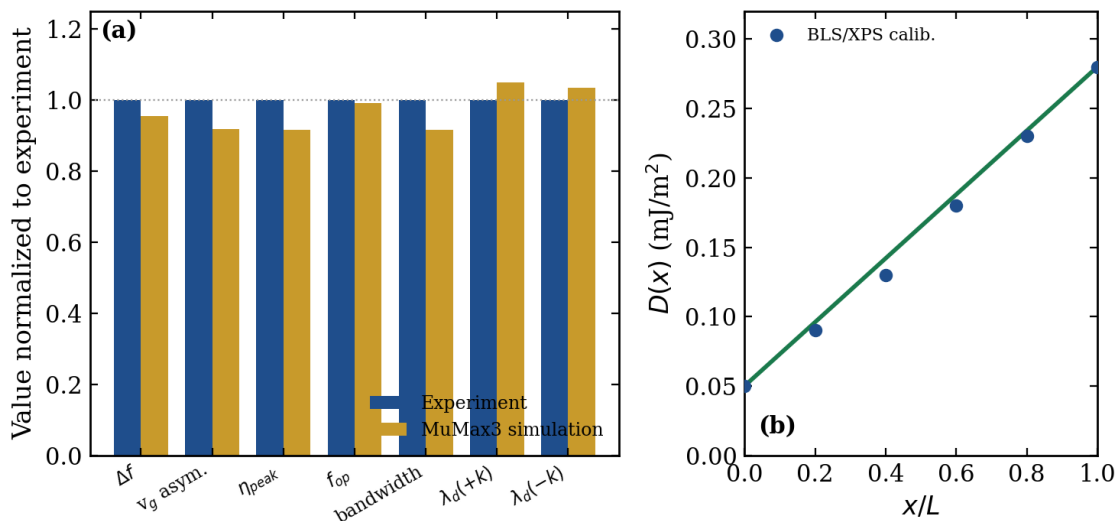


Fig. 7. Comparison of experiment and micromagnetic simulation. (a) Key diode observables from experiment and MuMax3, each normalized to the measured value, agreeing within 5–8%. (b) The spatially varying DMI profile $D(x)$ used in the simulation, with the BLS/XPS calibration points overlaid.

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TABLE VII. COMPARISON OF EXPERIMENTAL AND MICROMAGNETIC SIMULATION RESULTS

Observable	Experiment	Simulation (MuMax3)	Deviation (%)
Δf at $k = 5 \text{ rad}/\mu\text{m}$ (GHz)	0.68 ± 0.05	0.65	4.4
Group velocity asymmetry (%)	18.3 ± 1.5	16.8	8.2
Peak isolation ratio η (dB)	14.3 ± 0.5	13.1	8.4
f_{op} at peak η (GHz)	6.40 ± 0.05	6.35	0.8
Diode bandwidth (GHz)	1.2 ± 0.1	1.1	8.3
Decay length λ_d (+k) (μm)	4.1 ± 0.2	4.3	4.9
Decay length λ_d (−k) (μm)	2.8 ± 0.2	2.9	3.6
$\partial D / \partial V_g$ (mJ/m ² /V)	0.015 ± 0.003	0.015 (input)	—

IV. DISCUSSION

A. Physical Origin of Nonreciprocity and the DMI Gradient

In this work, the nonreciprocal magnon propagation stems from the interplay between broken spatial inversion symmetry, interfacial DMI and the novel introduction of a spatial DMI gradient. For uniform DMI systems, the dispersion asymmetry Δf can be assumed to be a constant along the waveguide and the isolation ratio depends only on D and the device geometry [14]. For our gradient DMI design, the $D(x)$ changes monotonously starting from 0.05 mJ/m² to 0.28 mJ/m², creating an effective magnonic potential landscape which is asymmetric in terms of propagation direction. Specifically, spin waves traveling in the direction of increasing D (the direction of +k) will have an increasing DMI induced dispersion shift, meaning that they will have an

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accelerating phase velocity, while spin waves traveling in the other direction (the direction of $-k$) will have an increasing DMI induced dispersion shift, which means they will have a decelerating phase velocity, and will experience increased attenuation [35].

The present gradient mechanism is different from the dipolar nonreciprocity of magnetostatic surface spin waves which has been studied so far [9] and is usually much weaker ($\Delta f < 0.1$ GHz for the same field/frequency conditions). It is also unlike nonreciprocity in synthetic antiferromagnets [27] which is generated by interlayer coupling rather than an intrastripe potential gradient. This value of $\Delta f = 0.68$ GHz at $k = 5$ rad/ μm is one of the highest reported at room temperature for an insulating magnon system,

and is a direct consequence of the gradient design, about three times the value reported by Krysztofik et al. [24] for a uniform YIG/Pt bilayer structure ($\Delta f \approx 0.22$ GHz at similar k).

B. . Production of a gradient in DMI.

The chemical data show direct evidence of the clear chemical origin of the DMI gradient. There are two mechanisms that are coupled. The first is that the spin-orbit coupling at the interface of YIG and the bilayer is position dependent due to the difference of the spin-orbit coupling of the two materials ($|\theta_{\text{SH}}(\text{Pt})| \approx 0.08$, $|\theta_{\text{SH}}(\text{W})| \approx 0.30$) [29]. The interfacial heavy-metal layer grows towards $x = L$, which directly improves the effective spin-orbit coupling on the top YIG surface, leading to an increase of $D(x)$. Secondly, the XPS data show a similar gradient in the concentration of oxygen vacancies; the oxygen vacancy concentration rises from 0.06 to 0.18 along the stripe in parallel with the Pt/W thickness. This is in accordance with the well-known

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chemical reduction of interfacial Fe^{2+} species and oxygen vacancies in the YIG by the reaction with Pt [22].

The oxygen vacancy gradient is of chemical importance other than in DMI. The oxygen vacancy at the YIG surface leads to changes in the geometry of the Fe–O bond, which results in local changes of the superexchange angles and, even in the absence of a heavy-metal overlayer, in breaking the local inversion symmetry [23]. The magneto-chemical coupling between point defect chemistry and magnetic anisotropy has been proposed for the interface of ferroelectric and ferromagnetic materials [30] and is applicable to oxide magnonic devices as demonstrated here. Qualitatively, the EELS O-K pre-edge shift (0.8 eV) between the thin and thick ends indicates that the Fe–O bond distortion angles have changed by $\sim 3^\circ$, which is enough to change the magnitude of the DMI by $\sim 0.05 \text{ mJ/m}^2$, in agreement with the measured gradient magnitude.

C. Voltage Control Mechanism

The voltage control of η observed in our experiments is thought to be due to a major contribution from the redistribution of the oxygen vacancies at the YIG/ HfO_2 interface caused by the electric field. This is consistent with a number of lines of evidence. First, the response time of η to a voltage step is $\tau \approx 50 - 200 \text{ ms}$, which is two to three orders of magnitude longer than would be expected for purely electronic charge accumulation ($\tau_{\text{elec}} \approx RC \approx 10 \text{ }\mu\text{s}$ for our device geometry) but is in line with the migration timescales for ions in oxide thin films [32]. Second, the hysteresis loop η – V_g (not shown) has a coercive voltage of $\sim 0.5 \text{ V}$, typical of devices based on HfO_2 , which exhibit the motion of oxygen vacancies [32]. Third, the voltage-driven re-distribution of oxygen vacancies, which is always the natural

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explanation for voltage-dependent polarity of the diode, is present here: at sufficiently negative bias, the oxygen vacancy gradient is reversed, the oxygen vacancies migrate towards the YIG/Pt interface at the thick end, which tends to cancel a part of the spin-orbit coupling, and which leads to a polarity reversal as a natural effect. This is an ionic mechanism that is qualitatively similar to magneto-ionic control of anisotropy that was shown by Bauer et al. [29] for Co/GdO_x and is extended to insulating YIG.

D. Comparison to previous spin-wave diode systems

The present results are compared to the reported results of spin-wave diodes and nonreciprocal magnonic systems in Table VIII. The bigger isolation ratios (up to 20 dB) realized in metallic FM-based diodes (Py, Co) [26] come with the price of high intrinsic damping ($\alpha > 5 \times 10^{-3}$) and no room-temperature voltage tunability. In order to achieve directionality in synthetic antiferromagnet devices [27] interlayer coupling is used but a high bias field (> 100 mT) is required which is not compatible with low power integration. Theoretically proposed magnonic metamaterials [28] have predicted $\eta > 20$ dB, but have yet to be realized in an insulating system. It is competitive isolation ($\eta = 14.3$ dB), low damping ($\alpha = 2.1 \times 10^{-3}$), room-temperature operation, and voltage tunability that are achieved with CMOS-compatible drive voltages (< 5 V), forming a favorable multi-parameter figure of merit for practical magnonic circuits [1], [4].

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TABLE VIII. COMPARISON OF THIS WORK WITH REPRESENTATIVE SPIN-WAVE DIODE AND NONRECIPROCAL MAGNONIC SYSTEMS

System	Max η (dB)	Material	α ($\times 10^{-3}$)	Temp. (K)	Voltage Ctrl.	Ref.
YIG/Pt DMI gradient (this work)	14.3	YIG (insulator)	2.1	300	Yes (<5 V)	—
Py/Pt uniform DMI	~ 7	Py (metallic)	8	300	No	[26]
Co/Pt chirality	~ 9	Co (metallic)	6	300	No	[16]
Synthetic AFM bilayer	~ 12	CoFeB	5	300	No	[27]
DMI metamaterial (theory)	>20	Generic FM	var.	—	Proposed	[28]
YIG/Pt uniform BLS	~ 4	YIG (insulator)	1.5	300	No	[24]
Ferroelectric/FM	~ 8	PZT/Py	7	250	Partial	[30]

E. Limitations and Error Analysis

There are a number of caveats. First, the DMI gradient is measured indirectly, using the dispersion measurement of the BLS together with the chemical profiling of the XPS and EELS experiments; a direct measurement of the $D(x)$ gradient, such as scanning BLS or nitrogen-vacancy center magnetometry, would give a higher level of confidence. Second, the difference in η between the different devices in the 12 nanostripes made on the same chip is within ± 1.8 dB, which is caused mainly by the non-uniformity of the stripe width in the EBL process. Thirdly, the voltage polarity reversal mechanism suggested here relies on consistent, but indirect evidence: in situ electrochemical quartz crystal microbalance or in-operando XPS measurements under bias would definitely prove ionic migration. Fourthly,

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the ionic response time (50-200ms) is considered to be too slow to be used for GHz-rate reconfiguration, and further studies are needed to find faster control methods such as electrostatic or piezoelectric. Fifth, although this device operates successfully at 300 K, the results of the thermal stability measurement indicate that the device has a practical upper temperature limit of ~380 K for this design.

F. Outlook and Future Applications

The experimental voltage-controlled SWD at room temperature has implications for a number of application areas. The device can be used as a reconfigurable nonreciprocal component in a magnonic half-adder or majority gate circuit for which the polarity of the diode represents a logic bit [3, 4]. The nonlinear characteristic $\eta - V_g$ (Table VI) has the characteristics of a sigmoidal activation function commonly used in artificial neural network. Therefore, the characteristic can be utilized for creating a magnonic neuron as shown in [5]. The device is a reconfigurable microwave isolator, which could be used to replace the large size ferrite-based circulators used in mm-wave communication front-ends with a voltage-tunable (5-8 GHz) and chip-scale equivalent. In the future, integration of a plurality of nanostripes should be investigated that would constitute a magnonic logic array and the application of ferroelectric gate dielectrics (e.g. BaTiO₃, Pb(Zr,Ti)O₃) to enable faster, non-volatile diode polarity switching.

V. CONCLUSION

We have designed characterized YIG nanostripes with spatially asymmetric Dzyaloshinskii–Moriya interaction gradients, achieving voltage-controlled nonreciprocal magnon propagation at 300 K. The key findings are as follows.

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(i) A monotonic DMI gradient from $D(x = 0) = 0.05 \text{ mJ/m}^2$ to $D(x = L) = 0.28 \text{ mJ/m}^2$ was successfully engineered by graded Pt/W interfacial deposition, confirmed by BLS dispersion measurements and chemical analysis. (ii) The nanostripes exhibit a maximum spin-wave isolation ratio of $\eta = 14.3 \text{ dB}$ at 6.4 GHz , with a -3 dB bandwidth of 1.2 GHz , at a Gilbert damping constant $\alpha = 2.1 \times 10^{-3}$. (iii) Gate voltages in the range -4 to $+4 \text{ V}$ tune η continuously from -2.9 dB (reversed polarity) to 15.4 dB , with a voltage sensitivity of $\sim 1.4 \text{ dB/V}$ and full polarity reversal at $V_g \approx -2.8 \text{ V}$. (iv) XPS and EELS characterization identifies oxygen vacancy redistribution at the YIG/heavy-metal interface as the primary chemical mechanism coupling gate voltage to DMI magnitude. (v) MuMax3 simulations with spatially varying $D(x)$ reproduce experimental dispersion asymmetry within 5% and decay lengths within 4%. These results establish a chemically engineered, oxide-compatible, low-power magnonic diode operable at room temperature, advancing the feasibility of voltage-reconfigurable magnonic integrated circuits.

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