

Demonstration of on-chip all-optical switching of magnetization in integrated photonics

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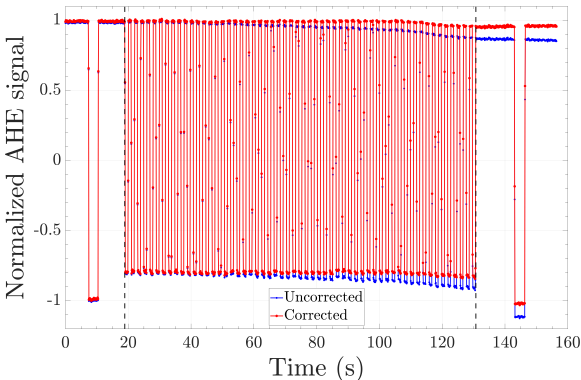
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S.I. A Linear Drift Correction

To ensure transparency, Supplementary Fig. 1 presents the raw anomalous Hall effect (AHE) signal (blue curve), normalized to the full magnetization swing as determined from external magnetic-field sweeps. At ~ 20 s, a femtosecond laser pulse train with a repetition rate of 1 Hz was applied in the absence of an external magnetic field, inducing toggle magnetization switching at the same rate via all-optical switching (AOS). During laser excitation, the AHE signal exhibits a gradual downward drift, which we attribute to localized absorption hot spots at the sharp edges of the Hall cross, leading to mild thermal degradation of the device. Importantly, this drift is non-magnetic in origin.

This interpretation is supported by external magnetic-field toggling performed both at the beginning (~ 15 s) and at the end (~ 140 s) of the measurement sequence without laser excitation. In



Supplementary Fig. 1 Raw (blue) and drift-corrected (red) normalized anomalous Hall effect signal.

both cases, the full magnetization swing is preserved, demonstrating that the intrinsic sensitivity of the Hall cross remains unchanged.

For clarity, a linear background correction was applied to the laser-excited data to remove the non-magnetic drift without altering the intrinsic toggle amplitude. The corrected signal (red curve) is shown alongside the raw data in Supplementary Fig. 1, ensuring that the representation of laser-induced toggle switching is not obscured by unrelated thermal effects.

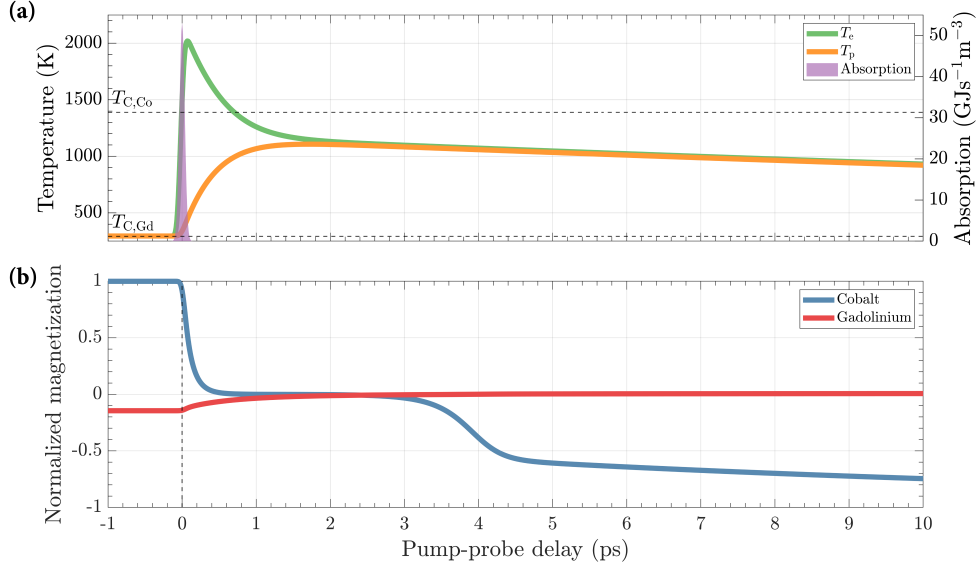
S.I. B Joined optical and magnetic model

To better understand the conditions required to induce all-optical switching (AOS) in a magnetic Hall cross integrated on a Si_3N_4 waveguide, we developed a simplified model linking optical excitation to magnetization dynamics. The results are shown in Fig. 2e. In ferrimagnetic materials, AOS critically depends on the absorbed optical power. To quantify this dependence, we employed the microscopic three-temperature model (M3TM) [19, 46], which, despite its simplifications, captures the essential energy exchange among electrons, phonons, and spins following ultrafast excitation.

Optical absorption in the Hall cross was determined using finite-difference time-domain (FDTD) simulations. The local absorption density was calculated from the divergence of the Poynting vector as

$$P_{\text{abs}} = \frac{1}{2} \omega |E|^2 \text{Im}(\varepsilon), \quad (\text{B1})$$

where ω is the optical frequency, E the electric-field amplitude, and $\text{Im}(\varepsilon)$ the imaginary component of the permittivity. The obtained absorption



Supplementary Fig. 2 Results of microscopic three-temperature model (M3TM) simulations for a Co/Gd system. **(a)** Temporal evolution of the electron (T_e , blue) and phonon (T_p , green) temperatures following optical excitation. The Gaussian pulse energy density (red) is derived from finite-difference time-domain (FDTD) simulations. Dashed lines indicate the Curie temperatures of cobalt ($T_{C,Co} = 1388$ K) and gadolinium ($T_{C,Gd} = 292$ K). **(b)** Corresponding relative magnetization dynamics of Co (blue) and Gd (red) on the same timescale, showing magnetization reversal in both layers with respect to their initial orientation.

datasets were used as input for the M3TM, assuming a Gaussian temporal profile for the laser pulse.

For this study, the model was reduced to a two-temperature model (2TM) description, sufficient to capture the coupled electron-phonon temperature dynamics (Supplementary Fig. 2a) that govern the final magnetic state (Supplementary Fig. 2b), while reducing computational cost and complexity. The full M3TM was employed to determine the minimum peak electron temperature ($T_{e,max}$) required to switch the magnetization of the Co/Gd system. This approach eliminates the need to recompute the full magnetization dynamics for each FDTD simulation cell, since the final magnetic state is uniquely determined by $T_{e,max}$.

The energy exchange between the electron (T_e) and phonon (T_p) systems is described by

$$\begin{aligned} \gamma T_e \frac{dT_e}{dt} &= g_{ep}(T_p - T_e) + P(t) \\ C_p \frac{dT_p}{dt} &= g_{ep}(T_e - T_p) + C_p \frac{(T_{amb} - T_p)}{\tau_d}, \end{aligned} \quad (B2)$$

where γ is the electronic heat-capacity constant, C_p the phonon heat capacity (Debye model), g_{ep} the electron-phonon coupling constant, τ_d the characteristic heat diffusion time, and T_{amb} the ambient temperature. The laser power $P(t)$ follows a Gaussian temporal profile centered at $t_0 = 4\sigma$ with standard deviation $\sigma = 50$ fs, and its amplitude P_0 is scaled to the absorbed power density P_{abs} from Eq. (B1).

As shown in Supplementary Fig. 2, the electron temperature (T_e , blue) rises sharply following excitation (red), followed by a slower phonon response (T_p , green) due to energy transfer. After thermal equilibrium is reached, the system cools through phonon-mediated heat diffusion to the substrate.

AOS occurs when the peak electron temperature ($T_{e,max}$) exceeds the Curie temperature of cobalt ($T_{C,Co} = 1388$ K) while the lattice temperature remains below it ($T_e > T_{C,Co} > T_p$). It should be noted that in magnetic thin films, the Curie temperature is typically much lower than the corresponding bulk value. Although the exact value is challenging to determine experimentally, using the bulk Curie

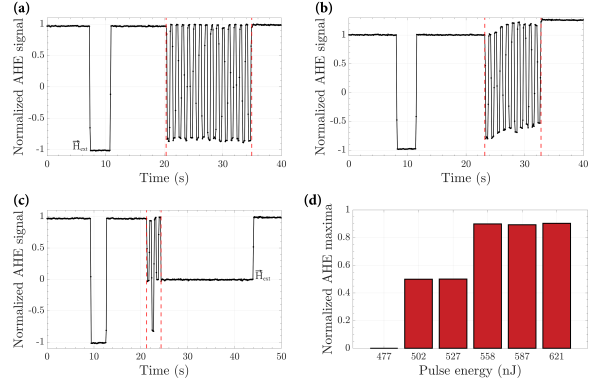
temperature in these calculations remains a reasonable approximation, as variations in T_C have only a minor influence on the relative magnetization trends observed. For the studied multilayer, Ta(2)/Pt(2)/Co(1)/Gd(3)/TaN(5)/Pt(2), where numbers in parentheses denote layer thicknesses in nanometers, simulations show that switching occurs when $T_{e,max} > 2020 \text{ K} > T_{p,max}$. The corresponding temperature and magnetization dynamics are shown in Supplementary Fig. 2. At higher excitation levels where $T_p > T_{C,Co}$, complete demagnetization occurs, and remagnetization becomes stochastic, resulting in a multidomain state. These temperatures, based on bulk Curie values, are expected to exceed those experimentally observed in thin films.

S.I. C On-chip AOS under varied input energies

We examined the on-chip all-optical switching (AOS) behavior following the *edge illumination* protocol for a range of pulse energies beyond the reference case of 621 nJ (E_0 , Fig. 2a) and 527 nJ (Fig. 2d). For the same Hall cross device, Supplementary Fig. 3 presents the time traces of the anomalous Hall voltage for optical excitation (between the red dashed lines) at pulse energies of (a) 586 nJ, (b) 558 nJ, and (c) 502 nJ. All traces are normalized to the initial magnetization swing induced by an external magnetic field which are also present in the figures.

As discussed in the main text, reducing the pulse energy below the stable-switching threshold prevents complete reversal of the Hall cross magnetization. Instead, the system stabilizes in a pinned intermediate state, where approximately half of the area probed by the anomalous Hall effect is switched. This behavior is particularly evident in Supplementary Fig. 3c, where the intermediate state remains stable between 25 s and 44 s until an external magnetic field is reapplied.

The average switched area was estimated by comparing the total anomalous Hall voltage change induced by the optical pulses to the voltage contrast obtained from full magnetization reversal under an external field. The corresponding results, shown in Supplementary Fig. 3d, indicate that the threshold pulse energy for stable complete switching of the Hall cross lies between 527 nJ and



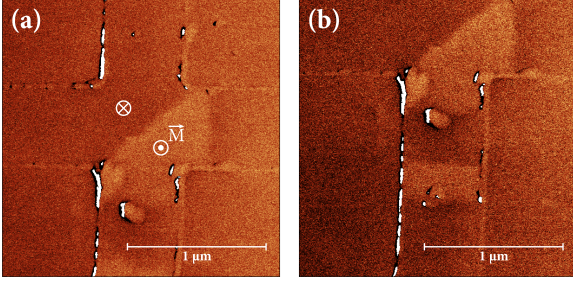
Supplementary Fig. 3 On-chip all-optical magnetization switching at different pulse energies. (a–c) Time traces of the anomalous Hall voltage recorded at pulse energies of 586 nJ, 558 nJ, and 502 nJ, respectively. The first two reversals are induced by an external magnetic field to define the saturation magnetization, to which all subsequent measurements are normalized. Between the red dashed lines, the magnetic field is removed and switching occurs purely optically under femtosecond light pulses at a repetition rate of 2 Hz. (d) Average fraction of the Hall cross area switched as a function of pulse energy, accounting for stochastic variations at lower energies.

558 nJ. At a pulse energy of 477 nJ, no AOS is observed.

S.I. D Visualization of magnetic domains

To further support the hypothesis that magnetic domain wall (DW) relaxation plays a role in predicting the final magnetic configuration of the Hall cross, as described in Fig. 3b, we experimentally visualized a partially switched magnetic state using magnetic force microscopy (MFM). The measurements, shown in Supplementary Fig. 4, were performed after *front-illumination* excitation with a 5.5 μm laser spot on a magnetic Hall cross (not integrated with the photonic platform) featuring 500 nm-wide arms.

For these measurements, an atomic force microscopy (AFM) tip was used, featuring a resonant frequency of 75 kHz, a cantilever spring constant of 2.8 N/m, and a tip radius of curvature below 10 nm. On top of the standard aluminium coating, an additional magnetic heterostructure of Ta(4)/Co(5)/Ta(4) (thicknesses in nanometers) was deposited on the cantilever by



Supplementary Fig. 4 Magnetic force microscopy of the Hall cross. (a) Central region and (b) one arm of the Hall cross after *front-illumination* excitation. Variations in orange hue correspond to opposite out-of-plane magnetization orientations as labeled in (a). The observed magnetic patterns indicate magnetic domain wall pinning at sharp corners and relaxation.

magnetron sputtering. The material of the Hall cross studied here differs slightly from those integrated into the photonic circuit and consists of Ta(4)/Pt(4)/Co(0.6)/Gd(1.2)/Co(0.6)/Pt(1.25)/Co(0.6)/Pt(4), providing enhanced magnetic contrast owing to its higher overall magnetic moment.

MFM imaging was performed in lifting mode, in which the Hall cross surface topography is first acquired in tapping mode and subsequently retraced at a fixed lift height to sense the long-range magnetic interaction between the tip and the sample stray fields. Basic post-processing, such as adjusting the colormap height range, was applied to enhance the visible magnetic contrast in the resulting images.

As shown in Supplementary Fig. 4a, the MFM image visualizes a partially switched magnetic state. The incident laser power was deliberately reduced to introduce stochasticity into the switching process, and the excitation was stopped once the anomalous Hall effect (AHE) signal indicated a partial reversal. A straight DW is clearly observed between oppositely magnetized regions, extending diagonally from the lower left to the upper right corner of the Hall cross. This configuration supports the proposed mechanism of magnetic relaxation and DW pinning at sharp geometric discontinuities. In the absence of apparent defects, the DW minimizes its total energy by straightening and becomes pinned only at the two corners of the Hall cross. In Supplementary Fig. 4b, an additional magnetic domain

appears in one of the Hall cross arms, consistent with the excitation spot slightly exceeding the central region. The final domain adopts a rectangular shape, further supporting the proposed mechanism that magnetic relaxation favors straight DWs, minimizing the DW circumference, constrained by the device geometry.

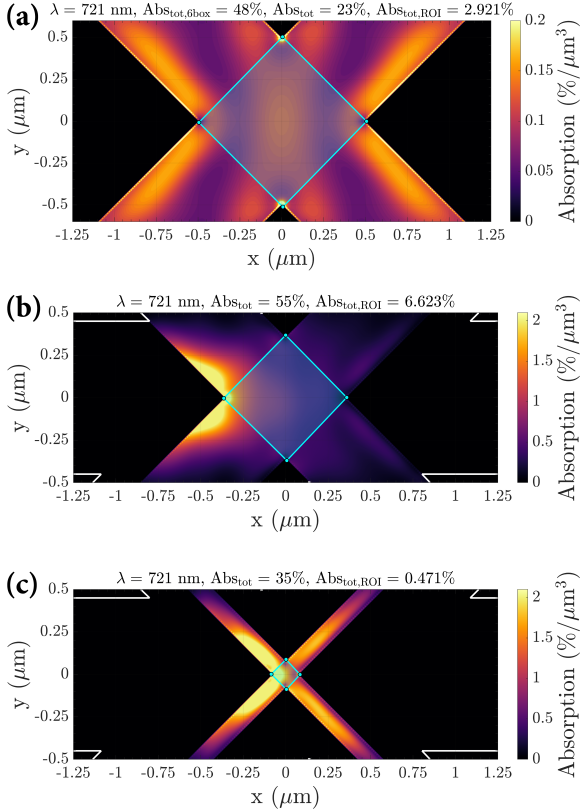
S.I. E Estimate of the switching energy

To estimate the switching threshold energy at scaled magnetic elements, we combine experimentally measured free-space all-optical switching (AOS) thresholds with finite-difference time-domain (FDTD) simulations of optical absorption.

Experimental free-space AOS measurements on a Co/Gd Hall-cross device with a 700 nm arm width yield a threshold switching fluence of approximately 5 mJ/cm². FDTD simulations of the optical excitation (Supplementary Fig. 5a), modeled as a plane wave to reflect the experimental condition where the laser spot size is much larger than the device dimensions, indicate that approximately 16% of the regional incident optical energy is absorbed within the Hall-sensitive region (highlighted in blue). This corresponds to an absorbed switching fluence of approximately 0.8 mJ/cm².

Assuming that switching is solely governed by the absorbed optical energy density within the Hall-sensitive region and scales linearly, the corresponding absorbed switching energy for a 500 nm Hall-cross device is estimated to be approximately 2.1 pJ. We then use FDTD simulations of the integrated photonic structure to determine the coupling efficiency from the fundamental transverse-electric (TE) waveguide mode into the Hall-sensitive region, visualized in Supplementary Fig. 5b. For the present device geometry, approximately 6.6% of the optical energy propagating in the waveguide is absorbed within the Hall-sensitive region (region-of-interest (ROI)). Consequently, the required in-waveguide pulse energy to reach the estimated switching threshold is approximately 32 pJ.

To assess the scaling behavior of the concept, we performed the same analysis for a 100 nm Hall-cross device while maintaining the same waveguide geometry. Owing to a more homogeneous absorption distribution within the active region,



Supplementary Fig. 5 Simulated optical absorption and scaling behavior of Hall-cross devices under free-space and waveguide excitation. Top-view absorption maps obtained from finite-difference time-domain (FDTD) simulations. The Hall-signal-sensitive region of interest (ROI) is highlighted in blue. **(a)** A 700 nm Hall-cross device under free-space excitation, modeled as a plane wave polarized along the y -direction. **(b)** A 500 nm Hall-cross device excited by the fundamental transverse-electric (TE) mode of a $900 \times 100 \text{ nm}^2$ Si_3N_4 waveguide. **(c)** A scaled 100 nm Hall-cross device under the same waveguide excitation conditions. The absorption fractions within the ROI and the entire Hall cross are indicated in each panel, illustrating how the overlap between the optical mode and the magnetic element evolves with device scaling. For panel **(a)**, the absorption calculated via a transmission box surrounding the device is additionally reported.

These estimates should be regarded as first-order values intended to quantify the energy requirements of the present proof-of-concept architecture. More advanced optical confinement schemes, such as photonic-crystal or plasmonic nanofocusing structures [32], are expected to substantially increase the fraction of optical energy delivered to the active region and thereby further reduce the switching input energy.

visible in Supplementary Fig. 5c, the required pulse energy is reduced to approximately 18 pJ. However, the improvement is significantly smaller than the geometric area reduction because the optical mode remains substantially larger than the interaction cross-section, limiting the scaling of the optical coupling efficiency.