process) on the characteristics of a magnonic directional coupler. Additional numerical simulations, similar to those shown in Fig. 6I (in the presence of a weak external magnetic field of 12 mT), were performed with rough boundaries (see Fig. 8B). Five-nanometer-wide and randomly defined long (from 50 to 400 nm to be comparable to the SW wavelength) rectangular magnetic elements are additionally introduced on both sides of each SW waveguide to act as roughness. The introduction of the roughness results in the increase of the average width of the waveguides. To compensate it, we increased the gap δ from 30 to 35 nm. Only a small difference in the operational characteristics of the directional coupler was found for different boundary conditions: The output power of the device is 99.3% for the smooth boundaries and 94% for the rough boundaries. These robust operational characteristics are due to the "diluted" SW dispersion spectra in the nanoscale waveguide shown in Fig. 2F, in which the frequencies of higher thickness and width modes are separated by several gigahertz. As a result, the elastic two-magnon scattering damping mechanism is absent (*19*, *21*). This is an additional advantage given to the directional coupler by its nanometer sizes.

CONCLUSION

In conclusion, a practical design of a nanoscale SW directional coupler is proposed and studied by means of micromagnetic simulations and analytical theory. The interference between the two collective SW modes of two laterally parallel and dipolarly coupled magnetic waveguides separated by a gap provides a mechanism responsible for the operation of the device. The coupling length L, over which the energy of an SW is transferred from one waveguide to the other, is studied as a function of the SW wave number, geometry of the coupler, relative orientation of the static magnetization in the coupled waveguides, and the magnitude of the applied magnetic field (if it is used). The proposed design of the device allows one to use it as a directional coupler, as a controlled multiplexer, as a frequency separator, or as a power divider for microwave signals. Our micromagnetic simulations have also shown that the proposed device has an additional benefit: Its functionality can be dynamically reconfigured within tens of nanoseconds by application of a short pulse of an external bias magnetic field. Finally, the robustness of the coupler has been tested in additional numerical simulations, where geometric sizes were varied. These simulations ensured us that the experimental realization of the device is possible. The nanometer sizes of the proposed directional coupler and its ability to operate without external bias field make the proposed device interesting and useful for the processing of both digital and analog microwave signals at the nanoscale.

MATERIALS AND METHODS

Extraction of the dispersion relations from the results of micromagnetic simulation

The micromagnetic simulations were performed using the MuMax3 (*39*) code. It uses the Dormand-Prince method (*51*) for the integration of the LL-Gilbert equation

$$\frac{d\mathbf{M}}{dt} = -|\gamma|\mathbf{M} \times \mathbf{B}_{\text{eff}} + \frac{\alpha}{M_s}\left(\mathbf{M} \times \frac{d\mathbf{M}}{dt}\right) \qquad (15)$$

where $\mathbf{M}$ is the magnetization vector; $\mathbf{B}_{\text{eff}}$ is the effective field that includes exchange, external, and demagnetization fields; γ is the gyromagnetic ratio; and α is the damping constant. The material parameters were given in the main text. There were three steps involved in the calculation of the SW dispersion curve in our simulation: (i) The external field was applied along the waveguide, and the magnetization was relaxed to a stationary state (ground state). This state was consequently used as the ground state in the following simulations. (ii) To excite odd and even SW width modes, a sinc field pulse was applied to a 20-nm-wide area located on one side of the waveguide. The sinc field is $b_y = b_0\text{sinc}(2\pi f_c t)$, with an oscillation field $b_0 = 1$ mT and a cutoff frequency $f_c = 20$ GHz. The $M_z(x, y, t)$ of each cell was collected over a period of $T = 100$ ns and recorded in $T_s = 25$-ps intervals, which allows a frequency resolution of $\Delta f = 1/T = 0.01$ GHz, whereas the highest resolvable frequency was $f_{\max} = 1/(2T_s) = 20$ GHz. The fluctuations in $m_z(x, y, t)$ were calculated for all the cells, $m_z(x, y, t) = M_z(x, y, t) - M_z(x, y, 0)$, where $M_z(x, y, 0)$ corresponds to the ground state obtained from the first step. (iii) To obtain the SW dispersion curves, we performed two-dimensional (2D) fast Fourier transformation (FFT) (*52*, *53*)

$$m_z(k_x, f) = \frac{1}{N}\sum_{i=1}^{N} |\mathcal{F}_2[m_z(x, y_i, t) - m_z(x, y_i, 0)]|^2 \qquad (16)$$

where $\mathcal{F}_2$ is the 2D FFT, y_i is the ith cell along the width of the waveguide, and N is the total number of the cells along the width of the waveguide. To visualize the dispersion curve, we recorded a 3D color map of $P(k_x, f) \propto m_z(k_x, f)$ in logarithmic scale versus f and k_x, which is shown in Figs. 2 (E and F) and 4 (A and B). We performed 2D FFT on the time evolution and along the waveguide. Next, the average FFT amplitude was taken along the width of the waveguide. This method allows us to obtain information about all the SW modes (even and odd) existing in the waveguide.

SUPPLEMENTARY MATERIALS

Supplementary material for this article is available at http://advances.sciencemag.org/cgi/content/full/4/1/e1701517/DC1

movie S1. SW propagation in coupled waveguides.

movie S2. SW directional coupler acts as a multiplexer.

movie S3. Switching of the device functionality by changing the bias magnetic field.

movie S4. Ground-state switching: parallel to antiparallel.

movie S5. Ground-state switching: antiparallel to parallel.

movies S6 to S8. The effects of temperature on the directional coupler properties.

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