

## Realization of spin-wave logic gates

T. Schneider,<sup>a)</sup> A. A. Serga, B. Leven, and B. Hillebrands  
*Fachbereich Physik und Forschungsschwerpunkt MINAS, Technische Universität Kaiserslautern,  
 67663 Kaiserslautern, Germany*

R. L. Stamps and M. P. Kostylev  
*School of Physics, University of Western Australia, Crawley, Western Australia 6009, Australia*

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We demonstrate the functionality of spin-wave logic exclusive-not-OR and not-AND gates based on a Mach-Zehnder-type interferometer which has arms implemented as sections of ferrite film spin-wave waveguides. Logical input signals are applied to the gates by varying either the phase or the amplitude of the spin waves in the interferometer arms. This phase or amplitude variation is produced by Oersted fields of dc current pulses through conductors placed on the surface of the magnetic films. © 2008 American Institute of Physics. [DOI: 10.1063/1.2834714]

Although commonly used for data storage applications, there have been relatively few attempts to employ magnetic phenomena for performing logical operations. The suggested concepts include the control of domain wall movement,<sup>1</sup> of magnetoresistance of individual magnetic elements,<sup>2</sup> and of a magnetostatic field of a set of magnetic nanoelements.<sup>3</sup> Yet another concept is using spin-wave interferometers. It was discussed theoretically in Refs. 4–6, but there was only one experimental demonstration of spin wave logic gate functionality,<sup>7</sup> where an one-input NOT gate was implemented in a interferometerlike geometry. In the present work, we experimentally demonstrate the functionality of more complicated logic gates based on spin waves.

The fabricated prototype of an exclusive-not-OR (XNOR, also called logical equality) logic gate is a direct extension of the NOT gate from Ref. 7 which was based on a Mach-Zehnder interferometer. For its implementation, the reference interferometer arm of the NOT gate is replaced by an arm identical to the signal arm. Controlling phases accumulated by the spin waves in both arms allows one to perform the XNOR operation.

Demonstrating the functionality of a not-AND (NAND) logic gate is a considerable step forward in the development of spin wave logic compared to the NOT and XNOR gates. Firstly, because the NAND function belongs to a class of universal functions which means that combining NAND gates allows one to construct gates of other types. Secondly, because for its implementation, we use here a different physical principle: direct control of spin wave amplitudes in the interferometer arms.

Figure 1(b) shows the principle setup of a XNOR gate. It consists of two arms of a spin-wave Mach-Zehnder interferometer implemented as ferrite film structures. Spin waves are inserted in both arms using microstrip antennas connected to a common microwave pulse source, thus guaranteeing the same phase in both arms. The spin waves are phase coherently detected using microstrip antenna detectors. The signals of both arms are brought to interference electronically. The phase accumulated by the spin waves on their paths through the two arms is controlled by applying dc currents  $I_1$  and  $I_2$  to the arms. Figure 1(a) shows phase inserted due to a

current in an interferometer arm. One sees a linear dependence of the accumulated phase on the current. One also sees that the phase characteristics in both arms are identical.

The currents  $I_1$  and  $I_2$  serve as *logical* inputs, where a logical zero is represented by  $I=0$  A and a logical one by the current  $I_\pi$ , necessary to create a phase shift of  $\pi$ . The microwave pulses at the *physical* input of the Mach-Zehnder interferometer represent rate pulses. The amplitude of the microwave interference pattern at the interferometer physical output serves as the logic output. Destructive interference (i.e., zero intensity) represents a logical zero and constructive interference (i.e., high intensity) represents a logical one. It is assumed that both arms are identical and thus both spin waves reach the output with identical amplitude and phase if no current is applied. If we now apply a current of strength  $I_\pi$  to one of the conductors (i.e., logical one to one input, zero to the other) one of the spin waves is shifted in phase by  $\pi$  which will lead to destructive interference (logical zero). If the currents in both conductors are identical (i.e., logical zero or one to both inputs), the interference will remain constructive (logical one). This behavior is summarized in the inset to Fig. 1(b). It resembles a XNOR gate.

The physical mechanism underlying the control of the spin-wave phase by a dc current through a conductor can be explained as follows. Due to the Oersted field of the conductor, the dispersion curve is shifted along the frequency axis and thus the carrier wavenumber of the spin-wave pulse is changed. This results in a change of spin-wave phase. The accumulated phase is linearly proportional to the current strength. As shown in Ref. 7, in the case of wide conductors, it is possible to shift the spin wave phase by  $\pi$  without introducing a noticeable decrease in the output spin wave amplitude due to reflection back from the region of induced field inhomogeneity.

To simplify demonstration of functionality of the XNOR gate, we used an upscaled prototype, compared to the common sizes of magnetic elements used in other logic schemes.<sup>2,3</sup> The physical principles underlying the device performance would remain practically the same if the prototype is implemented with micrometer sizes. As a medium for spin wave propagation, we use two 6  $\mu\text{m}$  thick and 1.5 mm wide yttrium iron garnet (YIG) spin-wave waveguides (see Fig. 1). In YIG films, spin waves can travel over several tens

<sup>a)</sup>Electronic mail: tschneider@physik.uni-kl.de.

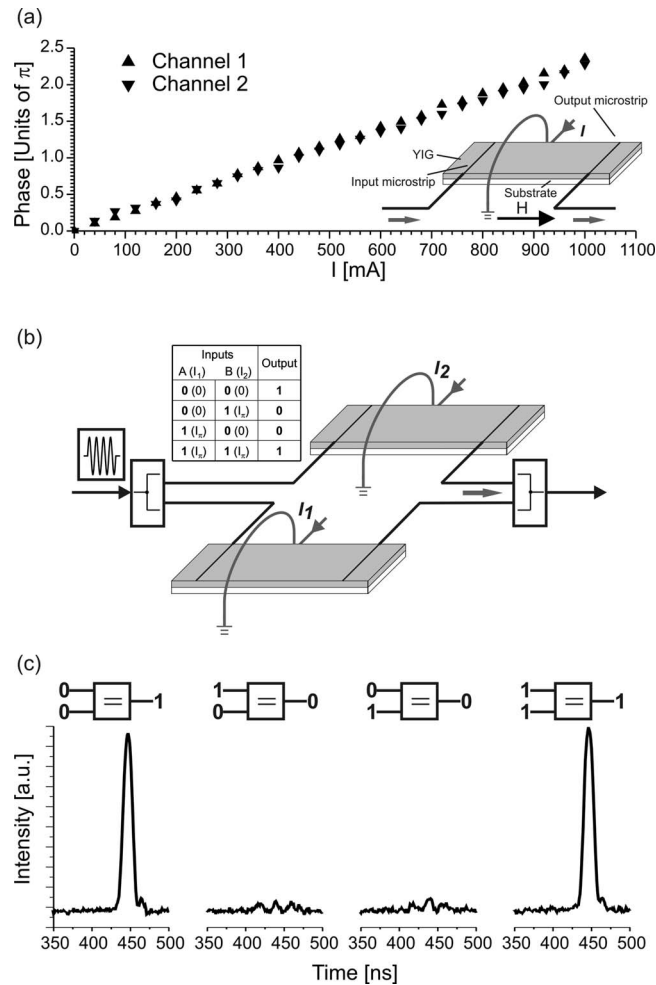


FIG. 1. XNOR gate. (a) Inserted phase vs current for the current controlled spin wave phase shifters (CPSs) used to construct the XNOR gate prototype. It is clearly visible that the phase shifts in both arms (channels) are identical. The inset shows the phase shifter geometry. (b) Spin-wave XNOR gate geometry. The currents  $I_1$  and  $I_2$  represent the logical inputs (0 A corresponds to 0,  $I_\pi$  corresponds to 1), the spin-wave interference signal represents the logical output. Inset: truth table for a XNOR gate. (c) Gate output signals for input signals shown in the diagrams.

of millimeters due to its extremely low magnetic damping. Conventional Permalloy films would allow for spin wave propagation over distances up to several tens of micrometers and are well suited for miniature devices.

Also for the sake of simplicity, the physical input and output of the Mach-Zehnder interferometer are implemented as microwave microstrip antennas. To transform microwave signals into spin-wave pulses in the YIG stripes and back into microwave signals, microwave transducers are utilized in the form of  $50 \mu\text{m}$  wide microstrip antennas placed 8 mm apart. (Note that the interferometer physical input and output can be implemented as all-spin wave waveguides, as shown in Ref. 4. This will make them compatible with a spin wave data bus, as recently suggested in Ref. 8. In such a structure, the microstrip transducers are not needed.) Wire loops (wire diameter is 0.5 mm) for spin wave phase control are placed between the input and the output microwave transducers. The spin-wave pulses in both interferometer arms are 20 ns in length. The microwave carrier frequency of the pulses is 7.132 GHz and the applied bias magnetic field is 1850 Oe. Control current pulses of 990 ns duration are applied to the conductors. Observe that the length of the current pulses can

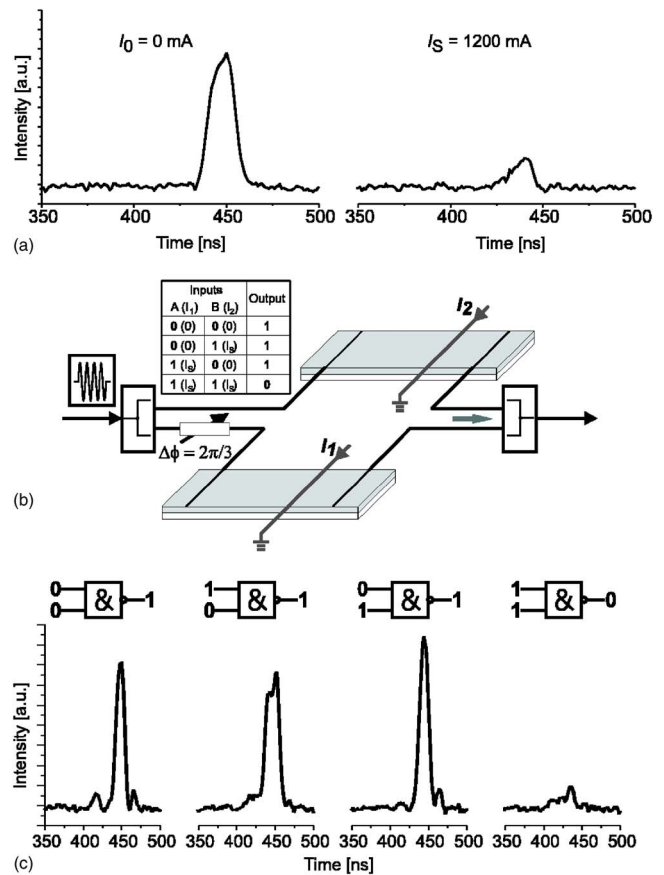


FIG. 2. NAND gate. (a) Demonstration of a spin-wave switch. Left part: output signal without applied current. Right part: output signal with applied current. Suppression of the output pulse is clearly visible. (b) Geometry of a spin-wave NAND gate. The currents  $I_1$  and  $I_2$  represent the logical inputs (0 A corresponds to 0,  $I_S$  corresponds to 1); the spin-wave interference signal represents the logical output. Inset: truth table for a NAND gate. (c) Gate output signals for input signals as shown in the diagrams.

be reduced to the length of the spin-wave pulses at the cost of an increased current necessary to create the  $\pi$  shift due to the then shorter interaction time.

Figure 1(c) demonstrates the microwave signal at the output of the prototype gate for different input configurations. The expected behavior is clearly visible.

In our previous works,<sup>9,10</sup> we show that one can control the spin wave amplitude by inserting a highly localized magnetic field inhomogeneity. The inhomogeneity can be created by a dc current through a narrow conductor placed on the surface of a ferrite film. A conductor with a width of  $100 \mu\text{m}$  produces a highly localized Oersted field. Independently of the sign of this additional Oersted field with respect to the applied static field, a spin-wave pulse can be reflected efficiently from such a strong inhomogeneity. In this work, we choose the current direction which produces an Oersted field in the direction opposite to the applied field. By applying a relatively small current, it is possible to shift the dispersion curve so that the carrier frequency of the spin wave pulse incident onto the inhomogeneity is no longer inside of the frequency band of spin waves. Spin waves cannot propagate through this prohibited zone, they can only tunnel. This introduces a strong back reflection of the incident pulse and one observes a strong change in the intensity of the spin wave.<sup>9</sup> It is important to notice that one can reduce the spin wave amplitude to nearly zero and, thus, use this setup as a

spin-wave switch. The functionality of such a switch is experimentally demonstrated in Fig. 2(a).

The realization of a logic NAND gate is demonstrated in Fig. 2(b). The setup mainly consists of a Mach-Zehnder interferometer, but this time, the phase shifters in the arms are replaced by switches. Similar to the XNOR gate, the logical output is implemented by the interference signal, while the inputs are implemented by the currents. Logical zero is represented by  $I_0=0$  A, and logical one by the current  $I_S$ , necessary to suppress the spin wave pulse transmission.

Experimentally measured output interferometer pulses are shown in Fig. 2(c). If a current is applied to only one of the switches (logical one to one input, zero to the other), a microwave pulse of a large intensity is transmitted (logical one at the output). The same takes place if no current is applied to both arms (logical zero to both inputs). To ensure that the intensity of the output microwave pulse is the same in this case as in the two other cases of a logical one at the output an additional permanent phase shift of  $2\pi/3$  is introduced in one of the interferometer arms. In this prototype, we use an external coaxial microwave phase shifter. However, a current controlled *spin wave* phase shifter similar to the one implemented in the XNOR gate prototype [Fig. 1(b)] may be easily integrated into the ferrite film structure instead. Any other possibility to create an additional phase shift (e.g., make the spin-wave propagation paths in the arms differ by  $2\pi/3$  by slightly increasing the length of one of the arms or using a thin permanent magnet to apply a small additional bias magnetic field to one of the arms) is also possible. A current applied to both switches (logical one to both inputs) leads to a nearly complete suppression of the output signal (logical zero). The described behavior [summarized in the inset of Fig. 2(b)] is the one of a NAND gate.

In conclusion, we experimentally demonstrated the func-

tionality of universal NAND and a XNOR logical gate using spin-waves propagating in a magnetic film interferometer based on YIG. By changing the used spin-wave waveguides (e.g., to Permalloy), a downscaling of the presented devices down to micrometer-scale dimensions should be possible and would open up an approach to logic structures on the micrometer scale.

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