AIP | Journal of Applied Physics

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Citation: Journal of Applied Physics **104**, 053909 (2008); doi: 10.1063/1.2975235
View online: http://dx.doi.org/10.1063/1.2975235
View Table of Contents: http://scitation.aip.org/content/aip/journal/jap/104/5?ver=pdfcov
Published by the AIP Publishing

Conceptual design of spin wave logic gates based on a Mach–Zehnder-type spin wave interferometer for universal logic functions

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(Received 25 April 2008; accepted 1 July 2008; published online 12 September 2008)

We present conceptual designs of an emerging class of logic gates, including NOT, NOR, and NAND, that use traveling spin waves (SWs) in the gigahertz range and that are based on a Mach–Zehnder-type SW (MZSW) interferometer. In this MZSW interferometer, logical input and output signals are achievable by the application of currents in order to control the phases that are accumulated by propagating SWs and by either destructive or constructive SW interference, respectively. In this article, the operation mechanism underlying a NOT gate function using a single MZSW interferometer is described and demonstrated numerically. The MZSW interferometer can itself become a NOT gate and be combined in its parallel and serial configurations to form NAND and NOR gates, respectively, which represent emerging classes of universal logic functions for microwave information signal processing. © *2008 American Institute of Physics*.
[DOI: 10.1063/1.2975235]

I. INTRODUCTION

Recently emerging classes of logical operations based on a variety of magnetic phenomena have been proposed (only a few of which operations have been experimentally demonstrated), utilizing traveling spin waves (SWs),[1–7] moving domain walls,[8,9] and networks of physically coupled nanometer-scale magnets.[10] Among these, SWs traveling at ultrafast speed through a nanowire-type SW waveguide made of magnetic materials are a highly promising information signal for application in a variety of logic functions.[2–4,11–13] Quite recently, Kostylev *et al.*[5] demonstrated the performance of a prototype NOT logic gate. In addition, Schneider *et al.*[6] experimentally demonstrated not only a prototype XNOR logic gate but also a universal NAND gate. These works provide a promising step further in the realization of SW-based devices applicable to information storage and signal processing devices. In such SW logic gates, a Mach–Zehnder-type[1] SW (MZSW) interferometer is a common and basic unit, consisting of an SW emission source, a detector, and a phase shifter, all of which can be manipulated by electric circuits.[5,6] The wave properties of SWs, including their generation, propagation, dispersion, interference, and phase change controllable by electric signals, are crucial to the functionality of SW devices, as has been theoretically and numerically demonstrated.[4,11–13] Among those functions, reliable control of the phase of traveling SWs in the MZSW interferometer is most essential for logic operations based on the wave properties of SWs. Hertel *et al.*[2] suggested a means to manipulate SW phases by a domain wall that is placed on one of the SW waveguide's paths, along which SWs propagate separately. However, it is not easy to practically manipulate the presence of a domain wall in a magnetic nanowire SW waveguide. In our previous work,[4] we suggested, as the most promising means of manipulation, an application of dc current through a conductor that can induce Oersted fields around itself. The magnetic field, applied to the paths along which SWs are propagating, can change the phases of those traveling SWs to enable their destructive or constructive interference.

In this article, we propose a simple MZSW interferometer NOT logic gate. This proposed logic gate can be used as a basic unit for any other types of logic gate employed for universal logic functions; for example, two MZSW interferometers arranged in a parallel (serial) configuration are equivalent to a NAND (NOR) logic gate. We report, therefore, not only on how the MZSW interferometer operates as a NOT logic function but also on how such interferometers can be combined to realize logic functions including NOR and NAND operations.

II. MODELING AND MICROMAGNETIC SIMULATION

Figure 1 illustrates the proposed MZSW interferometer's geometry, which consists of a Permalloy (Py) one-body SW waveguide used to split SWs and propagate them into two upper and lower paths before merging them again for destructive or constructive interference on the right side in the same waveguide as the SW splitter. An SW phase changer (also called a shifter) is inserted as a conducting wire, arranged vertically between the two branches of the one-body SW waveguide (Fig. 1). In order to micromagnetically simulate the generation, propagation, and interference of SWs allowed in the waveguide, we used the object-oriented micromagnetic framework code,[14] which utilizes the Landau–Lifshitz–Gilbert equation of motion.[15] In order to produce SWs of a single harmonic frequency $f = 18$ GHz from the

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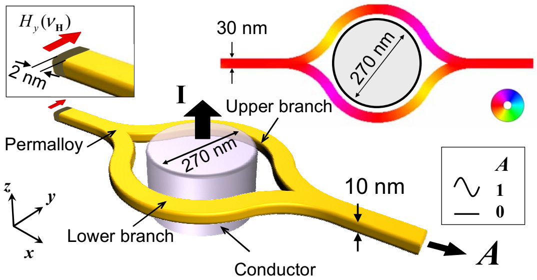

FIG. 1. (Color online) Perspective- and in-plane view illustrations of a MZSW interferometer composed of a Py bifurcated nanowire waveguide of width and thickness of 30×10 nm^2 and a conducting wire of 270 nm in diameter. The left and right ends of the waveguide indicate functions as the source and detector of SWs, respectively. The color in the plane view displays the local in-plane **M** orientation, as indicated by the color wheel.

left end, on only a rectangular 2×30 nm^2 region of the waveguide (inset of Fig. 1), we applied an oscillating magnetic field $\mathbf{H}=H_A \sin(2\pi\nu_{\mathbf{H}}t)\hat{\mathbf{y}}$ with $H_A=300$ Oe and $\nu_{\mathbf{H}}=18$ GHz along the y axis. The reason for choosing $f=18$ GHz is discussed below.

III. RESULTS AND DISCUSSION

First, in order to demonstrate the NOT logic function using the MZSW interferometer, SWs (Ref. 16) generated from the one end are allowed to be split into the upper and lower branches and again merged to interfere on the other end, without or with applying currents into the conducting wire. In the case of zero current density $J=0$, representing the logical input "0," the two merged SW beams constructively interfere with each other due to the lack of differences in phase and amplitude between the two, representing the "1" logical output [top of Fig. 2(a)]. By contrast, with currents of $J=2.0\times10^{11}$ A/m^2, the split SWs are merged to destructively interfere on the right end because they, after passing the upper and lower branches, become out-of-phase with each other, signifying the 0 logical output [bottom of Fig. 2(a)]. The value of $J=2.0\times10^{11}$ A/m^2 chosen here allows the split SWs to be out-of-phase for $f=18$ GHz. It is worth noting that the zero (a certain) current leads to a constructive (destructive) SW interference, indicating that the 0 logical input

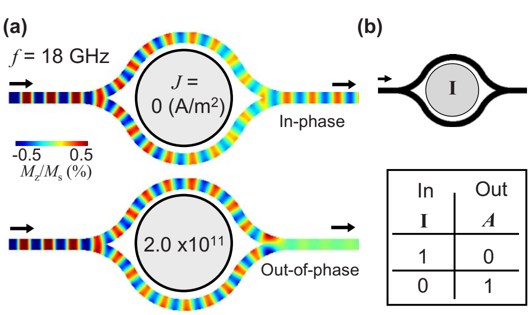

FIG. 2. (Color online) (a) Logical operations using SWs and based on a MZSW interferometer, which resemble the NOT logic function shown in (b). The snapshot in-plane images display the dynamic evolutions of SW propagations for $f=18$ GHz at a time of $t=1.5$ ns for two different cases $J=0$ and 2.0×10^{11} A/m^2, which correspond to the 0 and 1 input signals, respectively. The in-phase constructive and out-of-phase destructive SW interferences correspond to the 1 and 0 logical outputs, respectively, which are the same as the NOT logic function in (b).

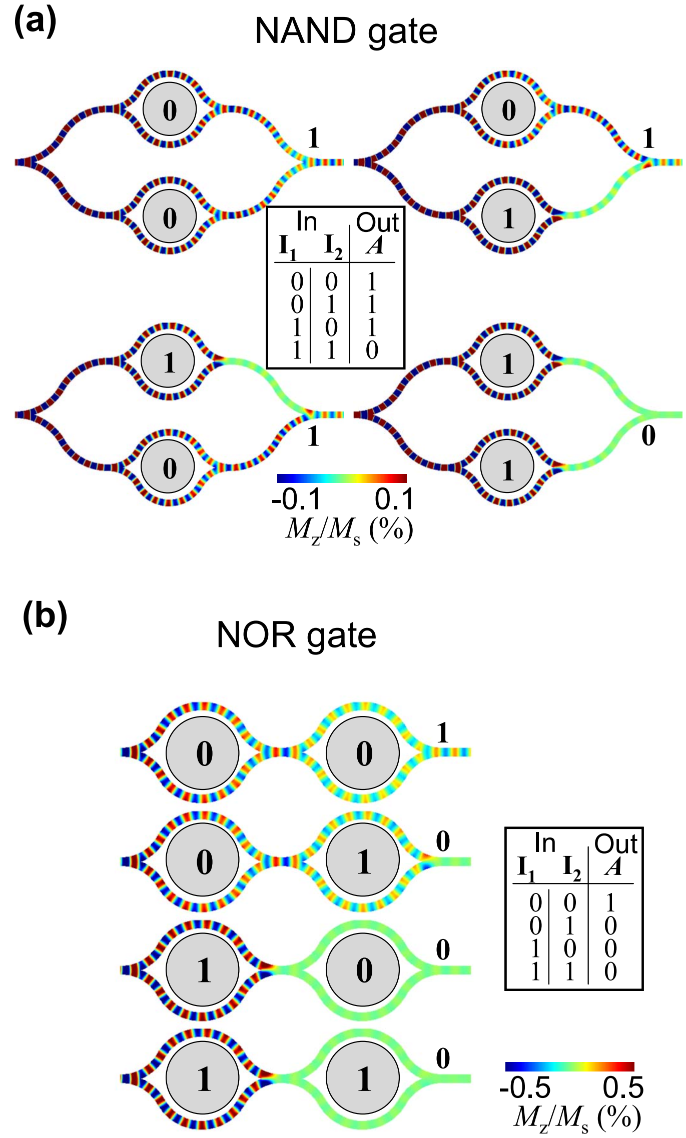

FIG. 3. (Color online) Logic operations (relations between the input and output signals) using SWs for a NAND gate in (a) and a NOR gate in (b). The NAND and NOR gates are composed simply of the two MZSW interferometers in parallel and serial configurations, respectively.

results in 1 output, whereas the 1 logical input yields 0 output. This logic function, illustrated in the table of Fig. 2(b), is known as NOT logic. Consequently, the MZSW interferometer can itself be used as a NOT logic gate using SWs. The operation principle of logical output based on the constructive and destructive interference of SWs has also been demonstrated experimentally as reported in Ref. 17.

Next, we numerically demonstrate the possible constructions of NAND and NOR gates by combining the two MZSW interferometers in the parallel and serial configurations, respectively, as shown in Fig. 3. As revealed by the snapshot in-plane images of the SW propagations along the MZSW interferometers, two independent inputs (I_1 and I_2) by the applications of electric dc currents to the two conductors lead to a 0 or 1 output signal according to the NAND or NOR logic operation (Fig. 3). The logic functions of both gates are listed in the logic tables shown in the insets of Fig. 3. The NAND or NOR gate is sufficient to realize any combinational logical

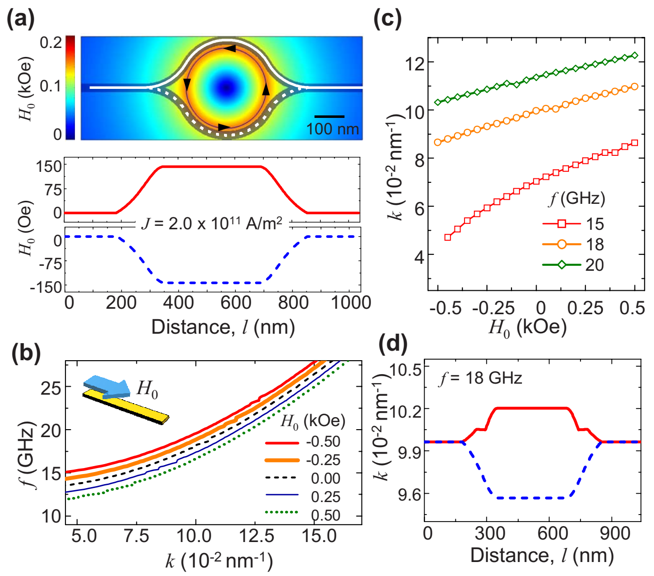

FIG. 4. (Color online) (a) Spatial distribution of the strength of the Oersted fields H_0 induced by currents flowing through the conducting wire and the field profiles along the upper (red solid line) and lower (blue dashed line) branches of the waveguide. The color bar indicates the field strength. The arrows on the circle indicate the direction of the Oersted field. (b) Dispersion curves of SWs allowed in the nanowire with a width and thickness of 30×10 nm^2 for the indicated different static fields. (c) k variation with H_0 for $f=15$, 18, and 20 GHz. (d) k profiles along the upper (red solid line) and lower (blue dashed line) branches of the waveguide for $f=18$ GHz.

function; that is, our proposed NOT gate, based on a single MZSW interferometer, is the unit block required for the construction of any type of SW logic gate.

Now we will discuss, on the basis of the underlying mechanism of the MZSW interferometer, the reason for the choices of $f=18$ GHz and $J=2.0\times10^{11}\,\text{A/m}^2$ in the demonstration of each of the logic functions. An application of electric current to the conducting wire results in an Oersted magnetic field H_0 around it, as illustrated in Fig. 4(a), where the spatial distribution of the H_0 strength and direction are indicated by the color bar and arrows, respectively. In principle, the magnetic field, applied to the waveguide along which SWs propagate, allows a shift in the dispersion of frequency versus wave number (f versus k) along the f axis for those SW modes allowed in the given geometry and material [Fig. 4(b)], which in turn yields the k variation of the SWs traveling along the waveguide for a given f [Fig. 4(c)]. The k variations with H_0 for different f are shown in Fig. 4(c). Thus, according to the different H_0 profiles along the two different branches of the waveguide [bottom of Fig. 4(a)], the two split SWs experience opposing direction phase shifts during their propagations along the different paths [Fig. 4(d)] because in the two branches the directions of the fields applied by the conductor are opposite to each other.

As a result, the phase difference $\Delta\Phi$, accumulated during the separate SW propagations between the upper and lower branches, is given by $\Delta\Phi=\int k_{\text{upper}}(l)-k_{\text{lower}}(l)dl$.[5] The $\Delta\Phi$ value is controllable with varying J and also is variable for different f, as seen in Fig. 5(a). From the $\Delta\Phi$ versus J curves for various f, we can select a J value for each f, satisfying $\Delta\Phi=\pi$, as revealed by the M_z/M_s profiles [Fig. 5(b)], e.g., $J(10^{11}\,\text{A/m}^2)=1.16$, 2.0, and 2.32 for $f=15$, 18, and 20 GHz, respectively.

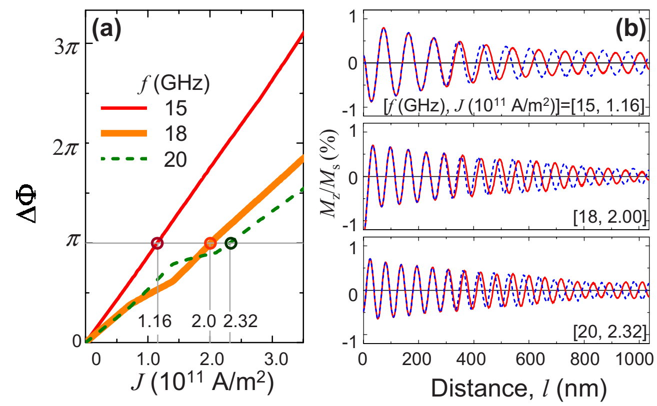

FIG. 5. (Color online) (a) Phase difference $\Delta\Phi$ as a function of J for $f=15$, 18, and 20 GHz. (b) Normalized out-of-plane component M_z/M_s profiles along the upper (red solid line) and lower (blue dashed line) branches for different sets of [f, J], as noted. The chosen [f, J] values correspond to $\Delta\Phi=\pi$.

IV. CONCLUSIONS

It is worth noting that the remaining issues with regard to the proposed MZSW interferometer NOT gate's use as a logic unit are the means by which destructive or constructive SW interference is monitored and by which low-power-consumption[13,18] strong SW signals are generated. Such relevant studies, now underway, are beyond the scope of this article, where we have proposed an MZSW interferometer logic unit that enables a NOT logic function using traveling SWs, in which the unit can be combined in serial and/or parallel configurations for emerging classes of universal logic gates applicable to a variety of logic functions.

ACKNOWLEDGMENTS

This work was supported by Creative Research Initiatives (Research Center for Spin Dynamics and Spin-Wave Devices) of MEST/KOSEF.

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