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MAGNETIC PLANAR WAVEGUIDES AS COMBINED POLARIZERS AND SPIN-FLIPPERS FOR NEUTRON MICROBEAMS

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Магнитные плоские волноводы как комбинация поляризаторов
и спин-флипперов для нейтронных микропучков

Предлагаются волноводные структуры, которые преобразуют входной неполяризованный пучок нейтронов в поляризованный микропучок, а также служат спин-флипперами, для чего изменяется угол скольжения входного пучка. Описываются оптимизированные структуры, сочетающие в себе эти функции. Такие волноводы могут быть использованы для исследования одномерных магнитных структур и применимы на любых существующих рефлектометрах с постоянной длиной волны нейтронов.

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Magnetic Planar Waveguides as Combined Polarizers and
Spin-Flippers for Neutron Microbeams

We propose the waveguides structures which transform an incident unpolarized neutron beam into a polarized microbeam and can also be used as spin-flippers by varying the incidence angle on the structure. We describe optimized structures combining these functions. Such waveguides could be used for the investigation of one-dimensional magnetic structures and implemented on any existing fixed wavelength reflectometer.

The investigation has been performed at the Frank Laboratory of Neutron Physics, JINR.

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INTRODUCTION

Continuing progress in nanotechnologies requires new characterization methods. Neutron scattering is a powerful method for the investigation of magnetic systems, polymers, and biological objects. However, the information one may obtain about the investigated structures is averaged over the width of the neutron beam which is typically of the order of tenths of a millimetre. Consequently, a variety of focusing methods (such as focusing monochromators, diffraction gratings, etc.) [1] have been developed to improve the spatial resolution of an experiment. These devices, however, are subject to physical and technological restrictions and can hardly provide focused spot sizes below 50 μm.

Planar waveguides are simple focusing devices which can produce a neutron beam of micron size width. The successful production of an unpolarized neutron microbeam using such a device was demonstrated in [2]. To investigate magnetic nanostructures with high spatial resolution, polarized neutron microbeams will be required. The production of polarized neutron microbeams was demonstrated experimentally in [3] using magnetic waveguides. Such neutron microbeams produced by planar waveguides have the shape of a long slit. The combination of a nonmagnetic waveguide and a polarized neutron reflectometer was also demonstrated in [4]. Polarized microbeams can typically be applied to study one-dimensional systems (wires, ripple domains, lithographic gratings, vortices in superconductors). In [5], we applied this combination for the investigation of a magnetic microwire [6] using a polarized microbeam. The method of the spin-precession transmission was used. This method was demonstrated for the investigation of domain walls in a film using the neutron macrobeam [7]. The inner magnetic structure of the wire 190 μm in diameter was scanned by a microbeam of width 2.6 μm. As the application of polarized neutron microbeams has been demonstrated in practice, we hope that the interest to find appropriate waveguides structures for particular situations may also increase. Therefore, in this communication we propose waveguide structures which transform an unpolarized incident neutron beam into a polarized microbeam and which can also act as spin-flippers. We describe the optimization of the parameters of such a device.

1. WAVEGUIDES ACTING AS POLARIZERS AND SPIN-FLIPPERS

The principle of a planar waveguide for a microbeam production is depicted in Fig. 1. A well collimated ($\sim 0.01^\circ$ divergence) but comparatively wide (~ 0.1 mm wide) neutron beam of intensity I_0 impinges on the surface of the waveguide (WG) under a glancing angle α_i. The simplest waveguide is a tri-layer structure characterized by a well-like neutron-optical potential with a thin top layer and a thick bottom layer. Neutrons tunnel through the upper layer into the middle guiding layer (or channel) of thickness d and are then partially guided inside this layer. Part of neutron beam goes out from the upper layer and is specularly reflected, and another part propagates along the guiding layer over a distance of a few millimeters. The distance, over which the neutron wave-function density decreases e times, is termed *channeling length* x_e. The theory of neutron channeling in planar waveguides can be found in [8]. The channeling length was measured experimentally in [9] and is of the order of several mm depending on the waveguide structure. Neutrons reaching the end of the waveguide structure leave the channel at the sample edge, forming a neutron microbeam whose spatial and angular characteristics are governed by Fraunhofer diffraction through a narrow slit. The initial width of the microbeam is equal to the channel width d.

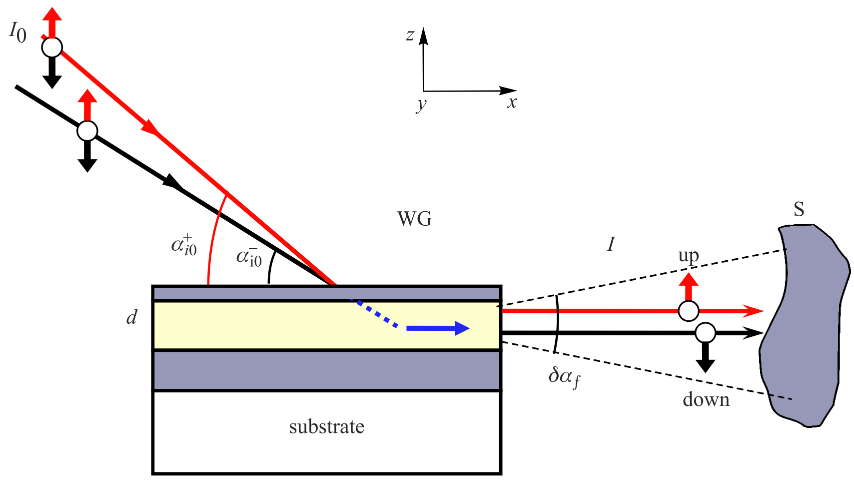

Fig. 1. Scheme of a neutron waveguide simultaneously acting as polarizer and spin-flipper: WG denotes the tri-layer waveguide structure resting on a substrate: I_0 is the intensity of the unpolarized incident neutron beam; $\Psi(z)$ is the neutron wave function inside the central guiding layer; I is the intensity of the polarized microbeam, and S is a magnetic nanostructure (sample) to be investigated. By suitably choosing the glancing incidence angle of the unpolarized macrobeam, it is possible to select up or down polarization of the microbeam with respect to the external magnetic field

The angular divergence of the beam is $\delta\alpha_f \sim \lambda/d$, where λ is the neutron wavelength. For example, for $d = 150$ nm and a neutron wavelength of 4.26 Å, the angular divergence of the microbeam is $0.14°$. The obtained microbeam can then be transmitted through the investigated microstructure (S).

As the microbeam is divergent, the investigated sample S has to be placed close to the waveguide so as to keep a minimal width of the microbeam to achieve the best spatial resolution. In the case of a magnetic microstructure S, a polarized microbeam should be used and the possibility of flipping the spin before the sample S is also needed. As the distance between the waveguide and the sample is about 1 mm, there is no space to put in a conventional macroscopic spin-flipper. This problem was solved by using a polarized incident macrobeam, a spin-flipper, and a nonmagnetic waveguide [4, 5]. We propose here another way, which does not require any polarizer or spin-flipper.

The theory of resonances in waveguides can be found in [10]. In the guiding layer, the neutron wave function density $|\Psi(\alpha_i)|^2$ is resonantly enhanced at some angles of incidence α_{in}, where $n = 0, 1, 2, \ldots$ are orders of resonances. The value of the angles of resonances depends on the neutron-optical potentials of the waveguide, the thickness of the guiding layer, neutron wavelength.

The idea of a waveguide combining the function of polarizer and spin-flipper is the following (Fig. 1). An unpolarized conventional beam enters the waveguide. It is possible to engineer the structure of the waveguide so that the resonance $n = 0$ appears at different incidence angles: $\alpha_{i0}^{+} \neq \alpha_{i0}^{-}$ for spin up/(+) and spin down/(–) neutrons. Thus, by switching between the incidence angles α_{i0}^{+} or α_{i0}^{-} the polarization of the microbeam can be chosen, because only spin up or spin down neutrons, respectively, will effectively propagate within the guiding layer. In other words, this concept allows one to produce a polarized microbeam from an unpolarized macrobeam and to reverse its polarization just by slightly tilting the incident angle of the macrobeam with respect to the waveguide. In practice, it is simpler to keep the incident beam fixed and rotate the waveguide.

2. PROPOSED STRUCTURE FOR THE REALIZATION OF POLARIZING/FLIPPING WAVEGUIDE

To realize the above-mentioned concept, we have numerically investigated the waveguide structure depicted in Fig. 2,*a* where the top layer and the substrate are made from the nonmagnetic alloy $Ni_{0.67}Cu_{0.33}$. These indices mean 67 at.% of Ni and 33 at.% of Cu in the alloy. This material has the highest neutron-optical potential available among nonmagnetic materials which turns out to be advantageous for our application. The nonmagnetic waveguide $Ni_{0.67}Cu_{0.33}$/Cu/$Ni_{0.67}Cu_{0.33}$//Si(substrate) was investigated in [4, 5]. For the application we discuss here, we suggest to use a $Co_{0.86}W_{0.14}$ alloy for the guiding

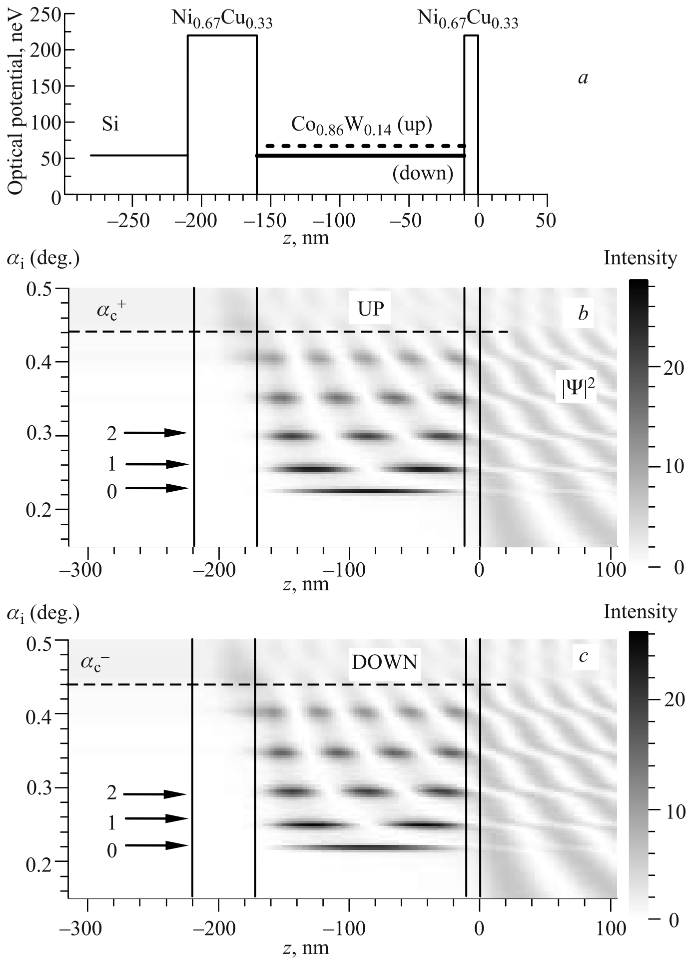

Fig. 2. *a*) Scheme of the neutron-optical potential of the waveguide $Ni_{0.67}Cu_{0.33}$(10 nm)/$Co_{0.86}W_{0.14}$(150 nm)/$Ni_{0.67}Cu_{0.33}$(50 nm)//Si(substrate) as a function of the depth coordinate z. The magnetization of the magnetic guiding layer $Co_{0.86}W_{0.14}$ was assumed to be 700 Gs. The dotted line corresponds to spin up neutrons; and the solid line, to spin down neutrons. *b*) Calculated wave function density inside the guiding layer for the spin up component. *c*) Corresponding wave function density for the spin down component

layer. This alloy has a sufficiently low nuclear potential (close to that of Co) and a particularly low saturation magnetization compared to the usual magnetic materials (Fe, Ni, Co). The saturation magnetization of this material can be varied by a small variation of the W concentration which is also an advantage. For a review of calculations and experimental results see [11]. For the alloy composition $Co_{0.86}W_{0.14}$, the saturation magnetization is as $M_s = 700$ Gs. The nuclear potential of $Ni_{0.67}Cu_{0.33}$ is equal to 220.5 neV, and that of $Co_{0.86}W_{0.14}$ is 61.8 neV. The total optical potential of $Co_{0.86}W_{0.14}$ is thus 66.0 neV for spin up (dotted line in Fig. 2, *a*) and 57.6 neV for spin down (solid line in Fig. 2, *a*).

The corresponding neutron wave function density $|\Psi(\alpha_i, z)|^2$ as a function of the glancing incidence angle α_i and the depth z below the sample surface is presented in Fig. 2, *b* for spin up and in Fig. 2, *c* for spin down. These calculations were performed with the program *SimulReflec* [12] for a neutron wavelength of 4.26 Å. One can clearly see the resonances $n = 0, 1, 2, 3$, and 4 below the critical angle of total reflection, $\alpha_c = 0.44°$. The angular divergence of the incident macrobeam was assumed to be $\delta\alpha_i = 0.006°$, and the wavelength resolution was assumed to be 700 G. The dotted line corresponds to spin up neutrons; and the solid line, to spin down neutrons. Calculated wave function density inside the guiding layer for the spin up component and corresponding wave function density for the spin down component are presented in Fig. 2, *b* and Fig. 2, *c*, respectively.

In Fig. 3, *a*, the calculation results for the specular reflectivity of the waveguide structure for spin up and down neutrons are presented as a function of the angle

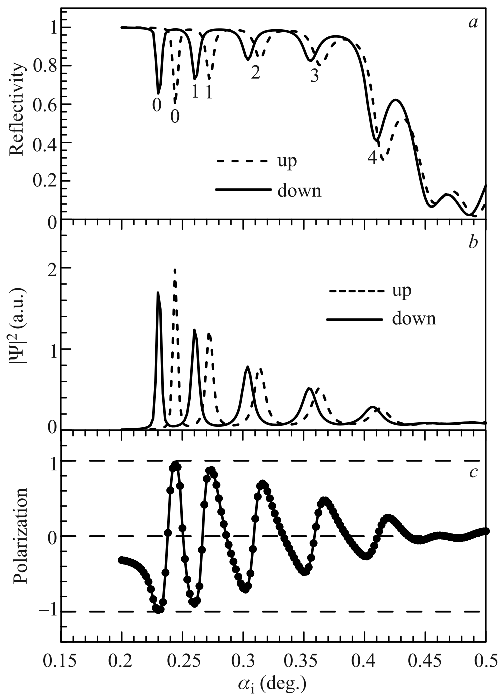

Fig. 3. *a*) Reflectivity for incident spin up (dotted line) and spin down neutrons (solid line) as a function of the incidence angle for the waveguide structure $Ni_{0.67}Cu_{0.33}$ (10 nm)/ $Co_{0.86}W_{0.14}$(150 nm)/$Ni_{0.67}Cu_{0.33}$ (50 nm)//Si(substrate) assuming a magnetization of 700 Gs for the guiding layer. *b*) Neutron wave function density integrated over the depth coordinate z within the guiding layer for the spin up (dotted line) and the spin down component (solid line) as a function of the incidence angle. *c*) Polarization of the microbeam (calculated from the neutron wave function densities for spin up and down within the guiding layer) as a function of the incidence angle

of incidence α_i. The dotted line corresponds to spin up; the solid line, to spin down. For each spin orientation, one can see five minima in the total reflection regime, at the positions corresponding to the resonances $n = 0, 1, 2, 3$, and 4 of the neutron wave function density in Fig. 3, *b* (integrated over the thickness of the guiding layer). The positions of the resonance $n = 0$ (Fig. 3, *b*) are $\alpha_{i0}^{-} = 0.230°$ for spin down and $\alpha_{i0}^{+} = 0.245°$ for spin up. The positions of the resonance n=1 are $\alpha_{i1}^{-} = 0.260°$ for spin down and $\alpha_{i1}^{+} = 0.275°$ for spin up. Most importantly, one can see that the angular position of the wave function maximum at the resonance $n = 0$ for spin up coincides with a wave function minimum between the resonances $n = 0$ and $n = 1$ for spin down.

The shape and the intensity of the neutron microbeam are defined by the neutron wave function density in the guiding layer [2]. Thus the polarization of the microbeam can be calculated by using the polarization of the wave function density integrated over the z coordinate within the guiding layer $(|\Psi^+|^2 - |\Psi^-|^2)/(|\Psi^+|^2 + |\Psi^-|^2)$. This quantity is plotted as a function of the incidence angle α_i in Fig. 3, *c*. For $\alpha_i = 0.230°$ the microbeam polarization is close to -1, whereas for the angle $\alpha_i = 0.245°$ the microbeam polarization is close to $+1$. Thus, by switching the incidence angle of the unpolarized macrobeam between 0.230° and 0.245°, it is possible to produce a highly polarized microbeam and to flip its polarization direction.

3. WAVEGUIDE STRUCTURE OPTIMIZATION

We describe here the way of optimizing the polarizing waveguide structure. The adjustable parameters are the saturation magnetization M and the thickness d of the guiding layer. For the optimization we use the following two criteria. The resonance position α_{i0}^{+} should lie in the middle between the resonance positions α_{i0}^{-} and α_{i1}^{-} in order to minimize the overlap between neighbouring resonances. In addition, the peak separation $\Delta\alpha_{i0} = \alpha_{i0}^{+} - \alpha_{i0}^{-}$ must be at least 0.015°. For a smaller angular separation, imperfections of the waveguide structure or nonideal experimental conditions may destroy the resonances or, at least, lead to a depolarization of the microbeam due to resonance overlap. The last constraint is given by the maximum divergence of the micro-beam one aims for.

Let us assume that we aim for a maximum divergence $\delta\alpha_f \sim \lambda/d$ of 0.14°. For a wavelength of 4.26 Å, the thickness of the channel should not be smaller than $d = 150$ nm. For this given thickness, it is possible to plot the neutron wave function density within the guiding layer as a function of the incidence angle for increasing magnetization values M. For the lowest magnetization of 300 Gs (Fig. 4, *a*), all the resonance peaks for spin up (dotted line) and spin down neutrons (solid line) are only slightly shifted with respect to each other by 0.01°. When the magnetization increases, the resonances peaks for spin up neutrons

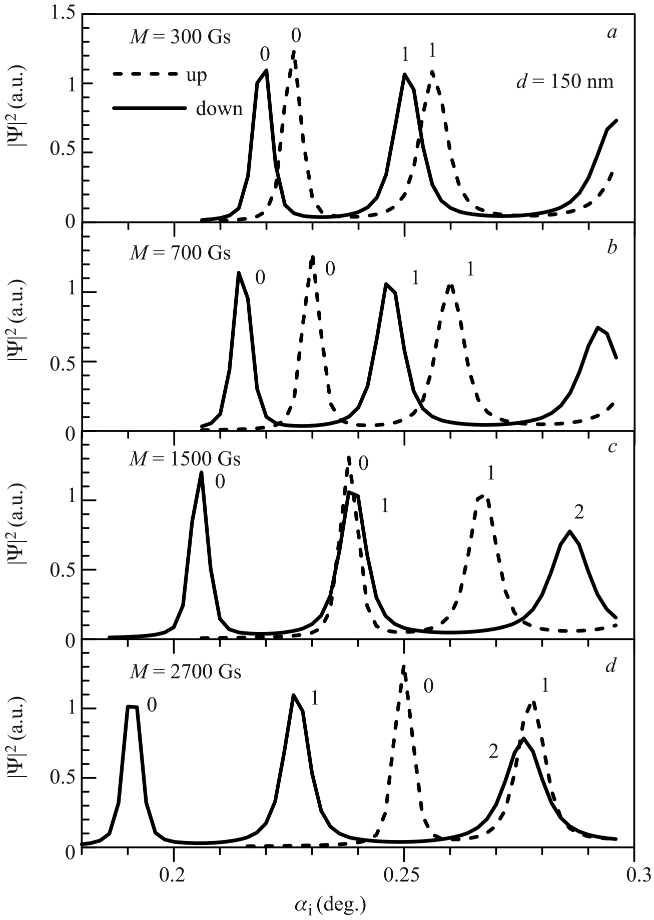

Fig. 4. Neutron wave function density (again partially integrated over z) plotted as a function of the incidence angle for fixed thickness $d = 150$ nm of the $\mathrm{Co}_{0.86}\mathrm{W}_{0.14}$ guiding layer and various magnetization values M: *a*) 300 Gs; *b*) 700 Gs; *c*) 1500 Gs; *d*) 2700 Gs

move to larger angles; and those for spin down neutrons, to smaller angles. For a magnetization of 700 Gs (Fig. 4, *b*), the resonance position α_{i0}^{+} is exactly centred between the resonance positions α_{i0}^{-} and α_{i1}^{-}. The peak separation $\Delta\alpha_{i0}$ is equal to 0.015° and therefore meets our second optimization criterion mentioned above. At a (hypothetic) magnetization of 1500 Gs (Fig. 4, *c*), the peak positions α_{i0}^{+} and α_{i1}^{-} coincide and the corresponding microbeam becomes depolarized. The microbeam may still be partially polarized, however, because of different output angle distributions for the resonances n=0 and $n = 1$. For a magnetization of 2700 Gs (Fig. 4, *d*), the resonance position α^{+}_{i0} has moved between the resonance positions α^{-}_{i1} and α^{-}_{i2}. The corresponding microbeam becomes again polarized.

Let us assume now that we can only produce a guiding layer with a magnetization of 1500 Gs. Figure 5 shows the resonance positions for various thicknesses of the guiding layer d. When decreasing the thickness d, the distance between resonances of different orders $n = 0, 1, 2, \ldots$ increases for both spin states up and down and both peak patterns move to larger angles. For the largest guiding layer

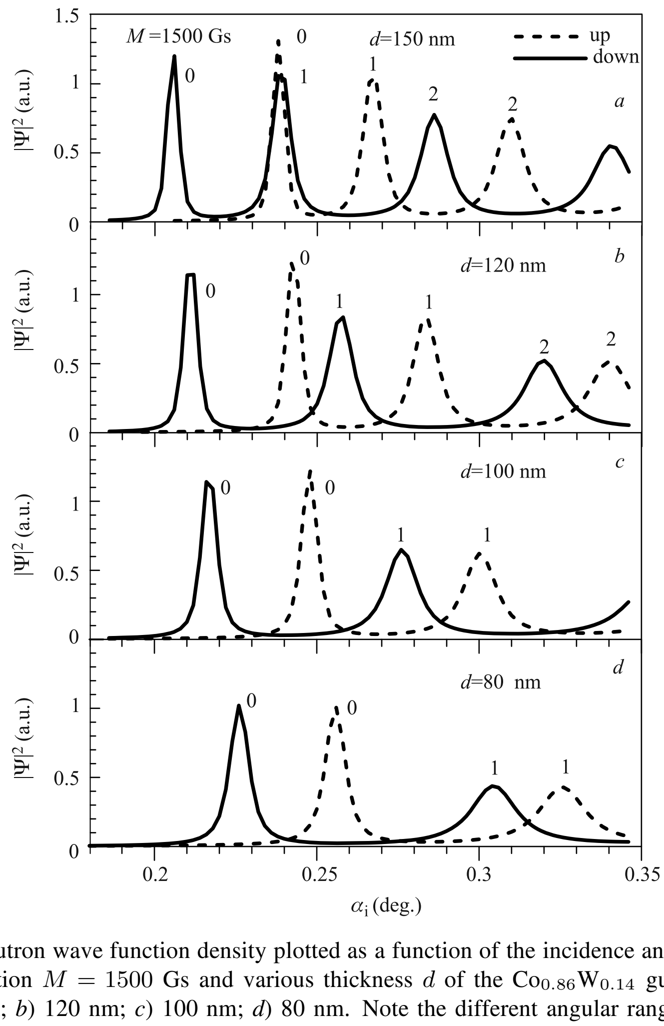

Fig. 5. Neutron wave function density plotted as a function of the incidence angle for fixed magnetization $M = 1500$ Gs and various thickness d of the $Co_{0.86}W_{0.14}$ guiding layer: *a*) 150 nm; *b*) 120 nm; *c*) 100 nm; *d*) 80 nm. Note the different angular range compared to Fig. 4

thickness $d = 150$ nm (Fig. 5, a), the peak positions α_{i0}^{+} and α_{i1}^{-} coincide and the corresponding microbeam is depolarized, at least partially. For $d = 120$ nm (Fig. 5, b), both peaks move to larger angles and separate from each other. For d=100 nm (Fig. 5, c), the peak position α_{i0}^{+} is optimally centred between α_{i0}^{-} and α_{i1}^{-} for the chosen magnetization value. However, the microbeam divergence governed by Fraunhofer diffraction increased up to 0.21°, which is 1.5 times larger than for the above thickness $d = 150$ nm. For $d = 80$ nm (Fig. 5, d), the resonance positions are also very well separated, but the microbeam is even more divergent.

The above calculations show that depending on the constraints (magnetization, divergence), it is easy to tune the other parameters so as to produce an optimal waveguide structure.

4. PRACTICAL OPERATION

For the operation of the proposed waveguide in a real experiment, the field applied on the waveguide structure must be decoupled from the field applied on the sample. The proposed technical solution is to install the waveguide structure in a closed magnetic circuit, built with permanent magnets, for example, to saturate the waveguide with a large field (1–2 kGs). This circuit might be placed in a small μ-metal box to reduce the stray fields (Fig. 6). This whole assembly shall be installed in larger magnetic coils so that it is possible to vary the field applied on the sample. This external field should, of course, remain lower than the field of the closed circuit so as to prevent a flip of the waveguide magnetization. The flip of the beam polarization is obtained by slightly tuning the incidence angle on

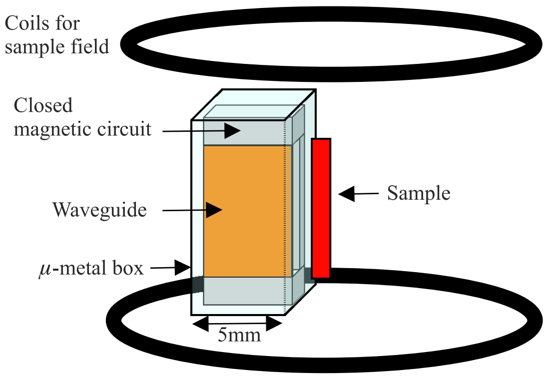

Fig. 6. Waveguide sample (typically 5 mm wide) in a closed magnetic circuit set in a μ-metal box. External coils allow varying the magnetic field applied on the sample

the waveguide structure, typically by varying the incidence angle from 0.230° to 0.245° to flip from *down* to *up* polarization. Such a setup could be readily used on any existing fixed wavelength reflectometer.

5. MAGNETICALLY TUNABLE DEVICE

In order to tune the position of the resonances and to avoid changing the angle to reverse the neutron polarization, one may consider, using ferrimagnetic materials, the alloys such as $TbCo_5$. In the case of ferrimagnetic materials, the saturation magnetization can be conveniently varied via the temperature. These alloys exhibit a vanishing macroscopic magnetization ($M = 0$ Gs) at the so-called magnetization compensation temperature. By reversing the macroscopic magnetization between two temperatures encompassing the magnetization compensation, the polarization of the neutrons will simply reverse for any given resonance position. The properties of $TbCo_5$ were investigated in [13]. The magnetization compensation temperature of this alloy is about 100 K, but it can be varied and even increased above room temperature by adjusting the stoichiometry of the alloy ($TbCo_4M$, $M = Al$ or Ga [14], or $TbCo_{3-4}$ [15]). The content and the neutron absorption of Tb are negligible and make the material suitable for neutron experiments. The extinction length of the wave guide is estimated to be around 2 mm which is a rather large value.

Tuning the magnetization of a ferrimagnetic guiding layer by temperature requires additional equipment to control the temperature of the waveguide. Consequently, the practical application of such waveguides for microbeam experiments on nanostructured samples may be complicated. But for the purpose of testing, adjusting, and optimizing waveguides, these materials may be quite useful.

CONCLUSION

We are proposing that planar waveguide structures may be used as a device producing a polarized microbeam whose polarization can be switched by slightly tuning the incidence angle on the structure. A magnetic material with low magnetization has to be chosen for the guiding layer. We propose to use $Co_{1-x}W_x$ alloys. The parameters of the structure can easily be tuned to meet the beam characteristics requirements, in particular, in terms of microbeam divergence. Such a device would be very compact (a few cm) and could be implemented on any existing fixed wavelength reflectometer. Using such a device, one-dimensional magnetic microstructures such as wires, ripple domains, or lithographic gratings may be investigated.

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