Optical Reading of Nanoscale Magnetic Bits in an Integrated Photonic Platform

Hamed Pezeshki®, Pingzhi Li®, Reinoud Lavrijsen, Jos J. G. M. van der Tol®, and Bert Koopmans, Member, IEEE

Abstract—In this paper, we propose a compact integrated hybrid plasmonic-photonic device for optical reading of nanoscale magnetic bits with perpendicular magnetic anisotropy in a magnetic racetrack on top of a photonic waveguide on the indium phosphide membrane on silicon platform. The hybrid device is constructed by coupling a doublet of V-shaped gold plasmonic nanoantennas on top of the indium phosphide waveguide. By taking advantage of the localized surface plasmons, our hybrid device can enable detection of the magnetization state in magnetic bits beyond the diffraction limit of light and enhance the polar magneto-optical Kerr effect (PMOKE). We further illustrate how combining the hybrid device with a plasmonic polarization rotator provides magneto-optical read-out by transforming the PMOKE-induced polarization change into an intensity variation of the waveguide mode. According to the simulation results based on a three-dimensional finite-difference time-domain method, the hybrid device can detect the magnetization states in targeted bits in a magnetic racetrack medium down to ∼100×100 nm², regardless of the magnetization state of the rest of the racetrack with a relative intensity contrast of greater than 0.5% for a ∼200×100 nm² magnetic bit. We believe our hybrid device can be an enabling technology that can connect integrated photonics with nanoscale spintrons, paving the way toward ultrafast and energy efficient advanced on-chip applications.

Index Terms—Photonic integrated circuits, plasmonics, spintronics, indium phosphide, magneto-plasmonics, polar magneto-optical Kerr effect.

I. INTRODUCTION

WITH the increase in demand for high bit-rate data transfer in the field of telecommunications and quantum information, the need for new technologies for high speed and reliable data reading and writing is foreseen. Advancements in

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Hamed Pezeshki, Reinoud Lavrijsen, and Bert Koopmans are with the Department of Applied Physics, Eindhoven University of Technology, 5612 AZ Eindhoven, The Netherlands, and also with the Center for Photonic Integration, Eindhoven Hendrik Casimir Institute, Eindhoven University of Technology, 5600 MB Eindhoven, The Netherlands (e-mail: h.pezeshki@tue.nl).

Pingzhi Li is with the Department of Applied Physics, Eindhoven University of Technology, 5612 AZ Eindhoven, The Netherlands.

Jos J. G. M. van der Tol is with the Center for Photonic Integration, Eindhoven Hendrik Casimir Institute, Eindhoven University of Technology, 5600 MB Eindhoven, The Netherlands.

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Fig. 1. The concept of the integrated device for all-optical reading of magnetic bits. (a) Left: a schematic diagram of the device illustrating the operation principle; right: the inset showing the transversal schematic diagram of the multilayer stack, comprising the magnetic racetrack. (b) Magnified view of the reading module showing the dimensions of the plasmonic nanoantenna elements and magnetic racetrack. The waveguide’s width and height are $w_1 = 570 \text{ nm}$ and $h = 280 \text{ nm}$ (see (a)), the racetrack width and height are $w_{\text{MR}} = 120 \text{ nm}$ and $h_{\text{MR}} = 10 \text{ nm}$, respectively; the length, width, and height of the plasmonic nanoantenna elements are $l_{\text{NA}} = 120 \text{ nm}$, $w_{\text{NA}} = h_{\text{NA}} = 30 \text{ nm}$, and they are oriented at $\theta = 45^\circ$ with reference to the waveguide direction. (c) Magnified view of the polarization rotator, where the width of the waveguide is $w_2 = 440 \text{ nm}$; the length, width, and height of the polarization rotator are $l_{\text{PR}} = 1860 \text{ nm}$, $w_{\text{PR}} = 180 \text{ nm}$, and $h_{\text{PR}} = 50 \text{ nm}$, respectively. “Ta”, “Pt”, “Co”, “NA”, “MR”, and “PR” stand for tantalum, platinum, cobalt, nanoantenna, magnetic racetrack, and polarization rotator.

IMOS platform. This allows the incident light propagating through the waveguide to be focused efficiently on the targeted nanoscale magnetic bit in the coupled racetrack and to enhance the naturally weak PMOKE response by improving the MO interactions with the magnetic bits. To detect the magnetic states in a targeted magnetic bit, the resultant polarization change induced by PMOKE is transformed into an intensity variation of the transverse magnetic (TM$_0$) waveguide mode [11] using our proposed plasmonic polarization rotator. Based on three dimensional finite-difference time-domain simulations, Lumerical, FDTD solver [12], we found that the presented hybrid device can enable the detection of the magnetization state in targeted bits in a magnetic racetrack medium down to a footprint of $\sim 100 \times 100 \text{ nm}^2$, without being disturbed by neighbouring bits. In contrast, for a photonic waveguide without the plasmonic nanoantennas, i.e. the bare waveguide device, this is not possible due to very weak PMOKE, while the extended waveguide mode would mix signals from neighbouring bits, ending up in ambiguous reading. Moreover, by using the polarization rotator, which works as an integrated quarter-wave plate, we show that the magnetic state in a magnetic bit with a size of $\sim 200 \times 100 \text{ nm}^2$ can be read-out optically with an intensity contrast of more than 0.5% only with using the hybrid device. The proposed device is a generic model which can be implemented in other photonic platforms such as silicon-on-insulator [13], [14] and silicon nitride [15], [16]. Based on our theoretical results, we believe that our proposed device concept can be an enabling technology which offers a method for direct optical reading of magnetic bits without intermediate electronics and it can be as well useful for magnet based sensing technologies.

II. DESIGN STRUCTURE AND FUNCTION PRINCIPLE
The schematic diagram of the proposed integrated device for optical reading of magnetic bits in a racetrack is shown in Fig. 1a. As depicted, the device consists of two sections:
the reading module and the polarization rotator section. The whole device is based on the IMOS technology [17]. The reading module is composed of a doublet of V-shaped gold plasmonic nanoantennas coupled with a magnetic racetrack as a top-cladding on the InP waveguide. A magnetic racetrack enables densely storing of information as up and down magnetization states [18], which can be moved along the racetrack by electrical current [19], [20], [21]. The racetrack is modelled as a multilayer stack (from bottom to top) of 4 nm ferromagnetic cobalt layer with a MO Voigt constant of $Q = 0.154-0.100i$ [22] (responsible for PMOKE in our simulation model), and a 2 nm platinum capping layer. A continuous wave laser light source with a free space wavelength of $\lambda_0 = 1550$ nm is coupled to the transverse electric (TE0) waveguide mode. Upon interaction between the TE0 waveguide mode and the plasmonic nanoantenna under the resonance condition, the localized surface plasmons of the plasmonic nanoantenna get excited and enhance the electric field at its nanoscale hot spot, where the magnetic racetrack is coupled. The concentrated electric field leads to an enhanced PMOKE. As the pure TE0 mode interacts with the magnetic cladding, partly a TM0 mode with a small magnitude is created due to PMOKE, whose phase is magnetization dependent, i.e. changes by 180° when the magnetization reverses. As a result of the birefringence in the waveguide, the TE0 mode and PMOKE-induced TM0 mode beat along the propagation distance. Therefore, the rotation and phase of this beating is magnetization dependent, i.e. changes by 180° when the magnetization reverses. In other words, we optimized our polarization rotator to perform as an integrated quarter-wave plate. The width of the polarization rotator is $w_{\text{PR}} = 180$ nm, and $h_{\text{PR}} = 50$ nm (where “PR” stands for polarization rotator), respectively, in order to match the quarter of beating length and rotate the eigenmode by 45°. In other words, we optimized our polarization rotator to perform as an integrated quarter-wave plate. The width of the waveguide in the polarization rotator section is reduced to $w_2 = 440$ nm to maximize the TE0 to TM0 conversion efficiency. Note that the refractive indices of the materials used in the model are taken from the built-in library of the Lumerical, FDTD solver [12]. The optical mode profiles at the cross section with the magnetic racetrack, i.e. in the YZ plane at X = 0, for the bare waveguide and hybrid devices, respectively. (c, d) The spatial field mode distribution cut-through the middle of the waveguide in the XY plane for the bare waveguide and hybrid devices. “MR”, “NA”, “SC”, and “WG” stand for magnetic racetrack, plasmonic nanoantenna, SiO$_2$ cladding, and waveguide, respectively.

**III. RESULTS**

In this section, we present the steps involved in the process of reading the magnetization state optically. The first step is based on PMOKE which is an induced change in the polarization state of the TE0 mode due to the MO activity. In the next step, we will convert the PMOKE-induced polarization change to an intensity variation of the TM0 mode which can be easily detected using an on-chip photodetector.

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**Fig. 2.** (a, b) The optical mode profiles at the cross section with the magnetic racetrack, i.e. in the YZ plane at X = 0, for the bare waveguide and hybrid devices, respectively. (c, d) The spatial field mode distribution cut-through the middle of the waveguide in the XY plane for the bare waveguide and hybrid devices are presented in Figs. 2c and 2d, respectively. Based on Fig. 2c, we can see that as light travels toward the polarization rotator, the change in the magnitude of the electric field is insignificant, due to a weak interaction between the magnetic racetrack and waveguide mode. In contrast, in the hybrid device, due to the enhanced light-matter interaction by the plasmonic nanoantenna, we can see a drop in the magnitude of the electric field of the propagating light toward the polarization rotator, as shown in Fig. 2d. These changes in the mode profile and magnitude of the electric field are consequences of the enhanced interaction between the waveguide mode and plasmonic nanoantenna, which ultimately results in enhanced MO response of the device.
the ratio of the magnitudes of TM0 to TE0, i.e., \( \Re(TM0/TE0) \).

Polarization rotation (Kerr rotation) defined as the real part of the first factor is the magnitude of the resultant PMOKE-induced optical reading using PMOKE based on two major factors. The first factor is the minimum footprint of the targeted magnetic bit in which the magnetization state can be identified regardless of all adjacent magnetic bits in the rest of the racetrack.

To investigate the minimum size of the targeted bit whose magnetization state can be determined, we perform a study of the evolution of the polarization rotation as a function of the size of the targeted magnetic bit, along the light propagation direction inside the waveguide. This analysis is done in the presence of the oppositely magnetized rest of the racetrack (see the inset in Fig. 3a). Here, we study the polarization rotation magnitude and phase as a function of the targeted bit size, by which the smallest readable bit size can be identified.

Figure 3a illustrates the evolution of the polarization rotation amplitude as the TE0 light mode propagates through the waveguide of the hybrid device, where the targeted bit has a domain width (DW) of 60 nm and is surrounded by the oppositely magnetized background (red domain in green background in the inset in Fig. 3a). As light interacts with the magnetic racetrack (orange region), we can clearly see a rise in the rotation of the polarization as a result of PMOKE. Here, we also note that the small polarization oscillation before the magnetic section is due to the light reflection from the plasmonic nanoantenna and the magnetic racetrack back to the input. Due to the birefringence in the waveguide, we have a beating between the TE0 mode and the PMOKE-induced TM0 mode which results in the oscillation of the polarization rotation magnitude as light propagates through the waveguide.

By increasing the width of the targeted bit (see Fig. 3b) and comparing the results, we can observe that not only the magnitude of the polarization rotation changes but also the phase varies. This change is such that the polarization rotation at DW = 60 nm is reversed by approximately 180° compared to DW widths of 200 and 570 nm. To explain the reason behind this reversal, it is important to note that the detected polarization rotation is the superposition of the contributions of both the targeted red domain and oppositely magnetized green domains. When the targeted bit width is very small, e.g. DW = 60 nm, the sum of the polarization rotations from the green domains dominate that of the targeted bit due to the small MO contribution from the targeted region. In this case, we cannot detect the magnetization state in the targeted bit unambiguously, since the outcome would depend on the content of neighboring bits. In contrast, when DW is either 200 nm or 570 nm (or any value in between), the polarization rotation of the targeted bit becomes larger than the sum of the polarization rotations of the oppositely magnetized regions. In this case, the magnetization state of the targeted magnetic bit can be uniquely identified.

Hence, we plotted the magnitude and phase of the polarization rotation for both the bare waveguide and hybrid devices as a function of DW in Fig. 4. As shown, a sudden transition in the phase of the polarization rotation is observed at DW for which the magnitude of the polarization rotation has a minimum. The minimum polarization rotation happens at DW = 120 nm (200 nm) for the hybrid (bare waveguide) device, which is accompanied by a jump in the phase of the polarization rotation. For very small DWs, i.e. DW < 120 nm (200 nm) in the hybrid (bare waveguide) device, the PMOKE response of the targeted bit is weaker than the superposition of the rest of the bits in the racetrack due to the limited MO contribution from the targeted region. Thus, the oppositely magnetized bits in green determine the magnitude and phase of the polarization rotation. On the other hand, for DW > 120 nm (200 nm), the PMOKE response from this bit (red domain) has become dominant. Thus, the magnetization state in the targeted magnetic bit can be explicitly identified above this value of DW, regardless of the magnetization state in the rest of the racetrack.

Based on the results, we can see that the minimum footprint for determining the magnetization state in the targeted bit is DW = 120 nm (200 nm) for the hybrid (bare waveguide) device, which is a measure for the resolution of the device.
Moreover, based on Fig. 4, we can see for larger target magnetic bits, e.g. DW = 570 nm, the enhancement in the polarization rotation is \( \sim 1.2 \times \). However, for target magnetic bits beyond the diffraction limit which is of our interest, e.g. DWs of 200 to 240 nm, the enhancement in the polarization rotation is larger by 5 to 13×, thanks to our designed plasmonic nanoantenna. Comparison of the performance of the bare waveguide and hybrid devices also indicates that the hybrid device enhances the resolution of magnetization read-out due to magneto-plasmonic effects beyond the diffraction limit. In general, this section illustrated the possibility of optically reading of the magnetization states in magnetic bits with subwavelength sizes of down to \( \sim 100 \times 100 \text{ nm}^2 \)\( \sim \)DW\( \times \)WMR\( \)), regardless of the magnetization state in the rest of the racetrack.

B. Detecting the Change in Magnetization State

As mentioned earlier, change in the magnetization state of the targeted bit induces a phase difference between the TE\(_0\) and emergent TM\(_0\) modes due to PMOKE. To be able to detect such a phase difference, we introduce a method for converting the phase difference to an intensity variation of the TM\(_0\) mode. In this way, the magnetization state is encoded in the TM\(_0\) intensity. As stated in section II, the polarization rotator section is comprised of a bilayer of SiO\(_2\)/gold (from bottom to top) which is asymmetrically positioned on top of the InP waveguide. The design parameters and schematic of the device are shown in Fig. 1c.

To get insight about transforming a phase change to an intensity variation of the TM\(_0\) mode using the polarization rotator, we use the polarization ellipse to illustrate the polarization states of the light mode with and without the polarization rotator. More explanation can be found in the previous work of our group [11]. The polarization state shown by the polarization ellipse can be quantified using the Stokes parameters \( S_1 \) to \( S_3 \) as follows [27]:

\[
S_1 = \cos 2\varepsilon \cos 2\theta, \quad (1)
\]
\[
S_2 = \cos 2\varepsilon \sin 2\theta, \quad (2)
\]
\[
S_3 = \sin 2\varepsilon, \quad (3)
\]

where \( \theta \) and \( \varepsilon \) are the polarization rotation (Kerr rotation) and ellipticity angle (Kerr ellipticity), respectively. The Stokes parameter \( S_1 \) to \( S_3 \) show that whether the light mode is a pure TE\(_0\) or TM\(_0\) mode (\( S_1 \)), an elliptically polarized mode (\( S_2 \)), or a circularly polarized mode (\( S_3 \)). Table I shows the values of polarization rotation (\( \theta \)) and ellipticity (\( \varepsilon \)) at the output of the bare waveguide and hybrid devices in terms of the magnetization states at DW = 200 nm, with and without the polarization rotator. This value of DW is chosen because DWs \( \leq 200 \text{ nm} \) is beyond the reach of the conventional optics (diffraction limit), which can be nevertheless breached by plasmonic nanoantennas. Based on Table I, the values of \( \theta \) and \( \varepsilon \) do not vary with the change in the magnetization state for the bare waveguide device with and without the polarization rotator. The reason is that at DW = 200 nm for the bare waveguide, the MO contribution is almost vanishing as shown in Fig. 4a which leads to \( S_1 \approx 1 \) and \( S_{(2,3)} \approx 0 \) for the cases of with and without the polarization rotator based on Eqs. 1 - 3. Figure 5a shows the polarization state of light (with some exaggeration for the sake of clarification) at the output of the hybrid device without the polarization rotator section for both up (red solid-line curve) and down (blue dashed-line curve) magnetization states, where two curves are overlapped. Based on the values of \( \theta \) and \( \varepsilon \) in Table I and Eqs. 1 - 3, the Stokes parameters are \( S_1 \approx 1 \) and \( S_{(2,3)} \approx 0 \) for both up and down magnetization states. In this case, the effect of PMOKE-induced polarization rotation is so small that it cannot alter the polarization state of the input mode significantly, and consequently we have a TE\(_0\) light mode without the polarization rotator section. On the other hand, Fig. 5b shows the polarization ellipse for the hybrid device in the presence of the polarization rotator section which shows the two curves do not completely overlap. According to Table I, the values of \( \theta \) and \( \varepsilon \) differ by 0.2° and 0.1°, respectively, when the magnetization state changes. Based on the values of \( \theta \) and \( \varepsilon \) in this case, \( S_2 \approx 0.8 \) and \( S_3 \approx -0.5 \) for both the magnetization states. In contrast, we have two slightly
different values of $S_1^{\uparrow} \approx -0.251$ and $S_1^{\downarrow} \approx -0.256$ for up and down magnetization states, respectively. This difference in the values of $S_1$ originates from a variation in the intensity of the PMOKE-induced TM$_0$ mode, which explains the phase to intensity transformation that is used to read out the magnetic bits. Hence, we defined a figure of merit $S_1$, i.e. the relative contrast of the TM$_0$ mode, as follows:

$$S_1(\%) = |S_1^{\uparrow} - S_1^{\downarrow}|.$$  (4)

Based on Eqs. 1 and 4, for the bare waveguide $\Delta S_1 \approx 0$. In contrast, our hybrid device offers $\Delta S_1$ of greater than 0.5% for the same targeted magnetic bit. One can see that using the bare waveguide, we cannot detect the change in the magnetization state in such a sub diffraction limit domain. However, our hybrid device with the help of magneto-plasmonic effects (offered by the proposed plasmonic nanoantenna) can overcome the diffraction limit and detect the magnetization change in a targeted bit size down to $\sim 100 \times 100$ nm$^2$ in the presence of oppositely magnetized neighboring bits. Note that the absorption losses by the plasmonic nanoantenna, magnetic racetrack, and polarization rotator are 8.68%, 9.45%, and 11.56%, respectively. The total reflection in the hybrid device is 4.84% and the transmission coefficient is 65.47%, which means that the insertion loss of the complete hybrid device is only -1.84 dB. As the signal to noise ratio (SNR) is inversely proportional to the square root of the insertion loss, from the performance perspective, we can see that this amount of insertion loss is acceptable.

IV. DISCUSSION

We numerically illustrated an ultracompact hybrid plasmonic-photonic device for optical read-out of the magnetization state in nanoscale magnetic bits. Using the hybrid device and a racetrack with a width of $\sim 100$ nm, the read-out of magnetic bits with a nanoscale size down to $\sim 100 \times 100$ nm$^2$ is possible using PMOKE, irrespective of the magnetization state in the rest of the racetrack. To complete the reading function, i.e. detecting the magnetization change on-chip, we proposed a method based on the polarization rotation principle. Our plasmonic polarization rotator transforms the PMOKE-induced polarization change in the TE$_0$ mode to an intensity variation of the TM$_0$ mode. Based on the simulation results, we showed that the hybrid device can detect the change in the magnetization state for a $\sim 200 \times 100$ nm$^2$ targeted magnetic bit with a relative contrast of greater than 0.5%, while the bare waveguide device is not able to detect.

During recent years, few groups have reported on enhancing PMOKE using plasmonic effects. Maccaferri et al. presented a periodic array of nickel nano-ellipsoids to enhance PMOKE using plasmonic resonance of this element [28]. It is noteworthy to mention that unlike gold, nickel cannot offer a strong plasmonic resonance as it suffers from a strong interband absorption at resonance condition [29]. Luong et al. demonstrated that in contrast to a titanium-cobalt composite nanohole array, a silver-cobalt composite nanohole array can provide larger PMOKE enhancement due to plasmonic effects offered by silver [30]. Freire et al. exhibited a PMOKE enhancement with growing a periodic 2D array of [cobalt/platinum]$_{10}$ (10 is the number of the repetition of the bilayer) on a gold metal layer [31]. In spite of reporting on improved PMOKE by these groups, the approaches introduced in these works are not ideally suitable for optically reading of nanoscale magnetic bits. In addition, from fabrication point of view, the integration of such structures to photonic integrated circuits is difficult. Very recently, our group demonstrated the first experimental
report on the on-chip MO reading of a diffraction-limited magnetic bit with a cross section of $600 \times 400 \text{ nm}^2$ and without the presence of oppositely magnetized nearby domains [11]. In contrast, to the best of our knowledge, this is the first illustration of optical reading of a nanoscale magnetic bit in the presence of an environment of arbitrary magnetized bits on an integrated photonic platform. Our proposed device concept, by offering MO read-out beyond the diffraction limit, can play a key role in the realization of the future technology of hybrid spintronic-photonic memories with energy efficient switching and reading with high bit-rate data transfer and data storage capacity.

V. CONCLUSION

We introduced an ultracompact integrated hybrid plasmonic-photonic device for optical reading of nanoscale ferromagnet bits having perpendicular magnetic anisotropy on the IMOS platform. The hybrid device, which is based on coupling a doublet of V-shaped gold plasmonic nanoantennas on top of the waveguide, strengthen the MO interaction beyond the diffraction limit of light with the help of magnetooptical effects. According to the simulation results, the hybrid device can make possible the identification of the magnetization state for $\sim 200 \times 100 \text{ nm}^2$ magnetic bits with a relative contrast of greater than 0.5%, but in general, targeted bits down to $\sim 100 \times 100 \text{ nm}^2$ can be unambiguously detected irrespective of the magnetization state in the rest of the racetrack. We believe this device can have a potential impact on direct optical read-out and can encode information in the optical state.

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Pingzhi Li received the M.Sc. degree from the Catholic University of Leuven (KU Leuven) in 2019, where his research focus was on the characterization of the performance of integrated SOT-MRAM. He is currently pursuing the Ph.D. degree with the Eindhoven University of Technology. He is an Early Stage Researcher funded by the Marie Skłodowska-Curie Actions Program of the European Commission. During his Ph.D. degree, his research focus is on the photonic control of spintronics.

Reinoud Lavrijsen is currently an Associate Professor with the Department of Applied Physics, Eindhoven University of Technology (TU/e). His areas of expertise include nanomagnetism and spintronics. His research currently focuses on making the switching of nanomagnets energy efficient by combining different emerging physical principles in a single device. Fundamentally, this opens many exciting research opportunities, such as the complex interplay between the driving forces. Specifically, the group is currently studying unexplored territories of spintronics; control of magnetization-dynamics by using synthetic-multiferroic-heterostructures. His objective is to obtain full control over the magnetization-dynamics of a (nano-) magnet without using magnetic fields. This is expected to result in a novel way of power-efficient and fast-coherent-control of magnetization. The potential for creating commercial devices (memory, data-storage, and logic) is huge and may create new paradigms in the fundamentals of the underlying physics by new ways of probing competing interactions in a cleverly chosen, simple materials/device system.

Jos J. G. M. van der Tol received the M.Sc. and Ph.D. degrees in physics from the State University of Leiden, Leiden, The Netherlands, in 1979 and 1985, respectively. In 1985, he joined KPN Research, where he had been involved in the research on integrated optical components for use in telecommunication networks. Since July 1999, he has been an Associate Professor with the Eindhoven University of Technology, Eindhoven, The Netherlands, where his research interests include opto-electronic integration, polarization issues, photonic membranes, and photonic crystals. He has coauthored more than 250 publications in the fields of integrated optics and optical networks and has 25 patent applications to his name. He has been working on guided wave components on III–V semiconductor materials. He has also been active in the field of optical networks, focusing on survivability, introduction scenarios, and management issues. His research interests include modeling of waveguides, design of electro-optical devices on lithium niobate, and their fabrication.

Bert Koopmans (Member, IEEE) received the Ph.D. degree from the University of Groningen in 1993. After a short stay as a Post-Doctoral Researcher at Radboud University Nijmegen, he spent three years as a Humboldt Fellow at the Max-Planck Institute for Solid State Physics, Stuttgart. In 1997, he joined the Eindhoven University of Technology, where he has been the Chair of the Group Physics of Nanostructures, since 2003. He participates in the NWO gravitation program on integrated nanophotonics, initiating research on hybrid spintronic-photonic devices. His current research interests include spintronics, nanomagnetism, and ultrafast magnetization dynamics. In 2020, he was elected as a Distinguished Lecturer of the IEEE Magnetics Society.