We experimentally investigate the application of magnetic fluids (MFs) on integrated silicon photonics. Using a ferrofluid-clad silicon microring resonator, we demonstrate active control of resonances by applying an external magnetic field. Relatively high loaded quality factors on the order of 6000 are achieved, despite the optical losses introduced by the magnetic nanoparticles. We demonstrate resonance shifts of 185 pm in response to a 110 Oe strong magnetic field, corresponding to an overall refractive index change of $-3.2 \times 10^{-3}$ for the cladding MF. The combination of MFs and integrated photonics could potentially lead to the development of magnetically controllable optical devices and ultra-compact cost-effective magnetic field sensors. © 2016 Optical Society of America

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Magneto-optic effects have been the subject of intense research efforts in recent years due to their important technological implications. They enable the construction of optical magnetic field sensors [1–6] that exploit the advantages of optics, such as immunity to electromagnetic interference and long-distance signal transmission for applications in geophysics, navigation, and medicine. Additionally, they allow the deliberate use of external magnetic fields to control the response of optical systems for various applications in optical systems, including optical isolation [7], light modulation [8–10], filtering [11–13] and Q-switching [14].

A significant share of the research on magneto-optic sensors and their applications has been focused on utilizing fiber-based systems with ferrofluids [4–6,15–17]. Ferrofluids, also called magnetic fluids (MFs), are colloidal solutions formed by superparamagnetic nanoparticles (NPs) dispersed in a carrier liquid [18]. In the absence of an external magnetic field, the single magnetic domain nanoparticles are randomly oriented in the carrier fluid due to Brownian motion. Under an external magnetic field, the magnetic dipoles align and tend to form structural patterns such as chains and columns (agglomeration of chains), significantly changing the optical properties of the MF [19–22]. The effects of the magnetic field can thus be assessed by modifications of the refractive index [23], field-dependent transmission [24], birefringence [25], or diffractive effects [26] of the MF. Despite extensive research in fiber-based systems, the applicability of MFs in integrated silicon photonics has not yet been demonstrated. Compared to fiber solutions, integrated silicon photonics provides the advantages of compactness, a CMOS-compatible fabrication process and good sensitivity enabled by high-quality-factor resonators [27]. In this Letter, we experimentally investigate the effects of MFs on silicon waveguide resonators. Specifically, we study the optical response of a microring resonator clad with a MF and demonstrate the control of the microring resonances by applying a weak external magnetic field. The application of MFs in an integrated platform can potentially lead to the development of magnetically controllable devices and ultra-compact cost-effective magnetic field sensors.

We demonstrate the magneto-optic effect on a silicon ring using a commercially available ferrofluid (Ferrotec USA, EMG901). It is composed of surfactant-coated Fe$_3$O$_4$ nanoparticles (10 nm nominal diameter) dispersed in kerosene. This commercial ferrofluid has a high volume concentration of NPs, around 11.8%, and is strongly absorbent for visible and near infra-red light. The original ferrofluid is diluted 15 times using a commercial immersion oil (Cargille, refractive index of 1.58) to achieve a concentration of 0.79%. The reduced MF concentration is chosen to exploit a trade-off between the magnetic field-dependent refractive index response and the induced optical losses. The response of the MF to an external magnetic field is depicted in Fig. 1. In the absence of a magnetic field, the NPs are randomly distributed in the fluid, and no particular organization is observed [Fig. 1(a)]. The fast Fourier transform (FFT) of the image confirms the absence of structural organization. When an in-plane magnetic field is applied using a magnet, the NPs originally dispersed in the liquid agglomerate to form columns oriented along the magnetic field direction [Fig. 1(b)] [24,28] (see also the FFT inset for the agglomerated structure image).

Our photonic device consists of a partially unclad silicon-on-insulator microring resonator of 100 μm radius [Fig. 2(a)]. The silicon waveguides (450 nm width by 250 nm height) are
defined using standard e-beam lithography and dry etching processes, also covered with a 1 µm thick cladding layer of PECVD-deposited SiO\textsubscript{2}. The deposited cladding is subsequently etched to expose most of the silicon microring resonator while maintaining the bus waveguides and the ring resonator coupling region protected. The device is then covered by a sub-10 µL droplet of the MF which acts as the top cladding of the exposed silicon microring. The gap distance between the microring and the input and the drop bus waveguides is 200 and 250 nm, respectively.

The operating principle of the magneto-optic device is illustrated in Fig. 2(b). In the absence of an external field, the NPs are randomly distributed in the fluid due to the Brownian motion. The MF is homogeneous and characterized by an initial average refractive index \( n_{\text{MF}} \) of 4.461 is obtained around wavelength of 1557 nm. At this wavelength, the loaded quality factor \( Q_L \) is \( \sim 30,000 \), and the resonances are critically coupled. This allows us to determine the experimental power coupling coefficient between the microring and the input waveguide \( \kappa_{\text{input}} = 0.172 \). This value is in good agreement with the coupling strength of 0.176 calculated by finite element method (FEM) simulations. Relying on such simulations, the coupling between the microring and the drop waveguide are estimated to be \( \kappa_{\text{drop}} = 0.073 \). Using these values of coupling coefficients and \( Q_L \), the propagation loss of the air-clad microring is estimated to be 7.7 dB/cm.

We characterize the optical response of the microring using the experimental setup illustrated in Fig. 3. A continuous-wave tunable laser source at telecommunication wavelength is coupled to the quasi-TE mode of the bus waveguide through a polarization maintaining fiber, and the transmitted light is detected and sent to the data acquisition (DAQ) module. The device under test is placed between two coils in Helmholtz configuration and subjected to a uniform magnetic field when the electric current generated by the current-voltage source flows through the coils. For the maximum available current of 620 mA, the Helmholtz coils generate a uniform magnetic field of approximately 110 Oe in the plane of the device. The tunable laser, current source, and DAQ are controlled via an automated measurement routine for fast data acquisition with a high spectral resolution of 0.2 pm. All measurements are performed at room temperature (25°C).

The transmission spectra of the device with air cladding and MF cladding are presented in Fig. 4(a). The air-clad device has sharp resonances separated by a free-spectral range corresponding to 0.865 nm, from which a group index \( n_{\text{air}}^g \) of 4.461 is obtained around wavelength of 1557 nm. At this wavelength, the loaded quality factor \( Q_L \) is \( \sim 30,000 \), and the resonances are critically coupled. This allows us to determine the experimental power coupling coefficient between the microring and the input waveguide \( \kappa_{\text{input}} = 0.172 \). This value is in good agreement with the coupling strength of 0.176 calculated by finite element method (FEM) simulations. Relying on such simulations, the coupling between the microring and the drop waveguide are estimated to be \( \kappa_{\text{drop}} = 0.073 \). Using these values of coupling coefficients and \( Q_L \), the propagation loss of the air-clad microring is estimated to be 7.7 dB/cm.
In the presence of the MF cladding, the resonances experience a ~35 nm redshift due to the increased effective index, and the group index slightly decreases to \( n_{g\text{eff}}^{\text{MF}} = 4.287 \). The high optical loss induced by the NPs lowers the \( Q_L \) to ~5, 200, and the propagation loss coefficient of the MF-clad ring is estimated as 120 dB/cm. The loss coefficient is calculated assuming the coupling coefficients \( k_{\text{input}} \) and \( k_{\text{drop}} \) remain unchanged since the coupling regions are protected by SiO\(_2\).

The relationship between the effective index \( n_{\text{eff}} \) of the quasi-TE mode of the silicon ring waveguide and the MF cladding index \( n_{\text{MF}} \), calculated by FEM, is shown in Fig. 4(b). Because of the high dilution of the ferrofluid in the immersion oil of index 1.58, \( n_{\text{MF}} \) remains in the range between 1.50 and 1.70. Thus, for a MF index around 1.60, the effective index is approximately 2.49, and it changes with the MF index at a linear rate of \( \frac{\partial n_{\text{eff}}}{\partial n_{\text{MF}}} = 0.188 \). This relation allows us to calculate the resonance shift \( \Delta \lambda_{\text{res}} \) associated with a given change in the MF index \( \Delta n_{\text{MF}} \) [30]:

\[
\Delta \lambda_{\text{res}} \approx f \cdot \frac{\lambda_{\text{res}}}{n_{g\text{eff}}^{\text{MF}}} \left( \frac{\partial n_{\text{eff}}}{\partial n_{\text{MF}}} \right) \Delta n_{\text{MF}}.
\]

In the above equation, \( f = 85\% \) is the fraction of the microring resonator exposed to the MF, \( \lambda_{\text{res}} = 1556.88 \) nm is the resonance wavelength, and \( n_{g\text{eff}}^{\text{MF}} = 4.287 \) is the group index of the MF-clad microring.

The microring spectral response to the external magnetic field is shown in Fig. 5. As the field increases, the resonances blueshift [Fig. 5(a)], and the quality factor increases due to a reduced interaction with the magnetic NPs, as described previously. For a uniform magnetic field in the range 0 to 110 Oe, no sign of saturation is observed, and the overall resonance shift is ~ -185 pm [Fig. 5(b)], yielding a sensitivity of 1.68 pm/Oe in this range. The corresponding overall change in the MF index calculated from Eq. (1) is \(-3.2 \times 10^{-3}\). As shown in Fig. 5(c), the loaded quality factor increases from ~5, 200 to ~6, 110 with the magnetic field, corresponding to a decrease in propagation losses from 120 to 100 dB/cm.

Figures 5(b) and 5(c) indicate that the microring spectral response is subjected to a hysteresis cycle as the external magnetic field is increased and then decreased, which we associate with a delayed response of the NPs. The complete measurement is performed relatively fast (30 s per field point) to mitigate the heating effects [31] induced by the nearby coils. Consequently, the magnetic NPs do not have time to retrieve their disordered distribution due to the viscosity of the fluid [32].

In conclusion, we have demonstrated the control of the optical response of an integrated silicon photonic microring resonator as a function of an externally applied magnetic field affecting MF cladding. For magnetic fields varying from 0 to 110 Oe, we observed resonance shifts of 185 pm, corresponding to a cladding refractive index change of \(-3.2 \times 10^{-3}\). This demonstration shows the possibility of combining readily available MFs and integrated photonics as a novel approach for compact and cost-effective magneto-optic devices.

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**Fig. 4.** (a) Normalized transmission of the ring resonator with air (red) and MF (blue) cladding. (b) Effective index of the quasi-TE mode as a function of the MF cladding refractive index. Inset: electric field profile for the quasi-TE mode.

**Fig. 5.** Microring response to the external magnetic field. (a) Transmission spectrum for increasing $B$. (b) Resonance shift and (c) loaded quality factor as $B$ is increased and decreased.
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