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Serge Vincent, Xin Jiang, Philip Russell, and Frank Vollmer

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Thermally tunable whispering-gallery mode cavities for magneto-optics

Serge Vincent,1,a) Xin Jiang,2 Philip Russell,2 and Frank Vollmer1,b)

AFFILIATIONS
1Living Systems Institute, School of Physics, University of Exeter, Exeter EX4 4QD, United Kingdom
2Max Planck Institute for the Science of Light, Staudtstrasse 2, 91058 Erlangen, Germany

a)Email: sv316@exeter.ac.uk
b)Author to whom correspondence should be addressed: f.vollmer@exeter.ac.uk

ABSTRACT
We report the experimental realization of magneto-optical coupling between whispering-galley modes in a germanate (56GeO2-31PbO-9Na2O-4Ga2O3) microspherical cavity due to the Faraday effect. An encapsulated gold conductor heats the resonator and tunes the quasi-transverse electric (TE) and quasi-transverse magnetic (TM) polarized modes with an efficiency of ~65 fm/V at a peak-to-peak bias voltage of 4 V. The signal parameters for a number of heating regimes are quantified to confirm sensitivity to the generated magnetic field. The quasi-TE and quasi-TM resonance frequencies stably converge near the device’s heating rate limit (equivalently, bias voltage limit) in order to minimize inherent geometrical birefringence. This functionality optimizes Faraday rotation and thus enables the observation of subsequent magneto-optics.

Optical devices that exploit whispering-gallery modes (WGMs) have gradually become ubiquitous.1 The WGM cavity has demonstrated strong optomechanical interactions,2,3 lased at ultralow thresholds,4 established parity-time symmetric systems,5 and detected single atomic ions near plasmonic nanoantennae.6 Tuning of WGMs outside of irreversible modification7,8 has been achieved by refractive index modulation, such as from mechanical strain/pressure,9–12 electro-optics,13–15 or thermal effects.16–20 Thermo-optical control is typically realized by selecting a high-thermo-optic coefficient material for the cavity18,19 or relying on absorption based heating,16,17 wherein the former involves an integrated heating element. Tuning of glass WGM cavities through an internal metallic conductor, however, can be intractable due to glass crystallization during fabrication. While melting the dielectric at a temperature below the conductor’s melting point, nucleation sites develop and with crystal growth inhibit WGM circulation. For sensing applications in a stochastic environment, there is also a need for laser jitter suppression when detecting nanoparticles21 and the removal of background drift when thermally characterizing polymers.22

By way of optomechanics and magnetostriction, on-chip WGM based magnetometers23 have detected magnetic fields as small as hundreds of pT/√Hz.24 More generally, magneto-optical coupling in a WGM resonator has been studied for transported magnetic fluids25,26 and for the resonator material itself.27 Cavity optomagnonics in yttrium iron garnet (YIG) microspheres28,29 offers coherent magnon-to-photon interconversion at optical and microwave frequencies, justifying the use of magnons as information carriers. An applied magnetic field $B$ modifies the cavity dielectric tensor by first and second order magnetization, respectively, known as the Faraday and Voigt effects.30 The quasi-transverse electric (TE) and quasi-transverse magnetic (TM) WGM resonance frequencies are split by the cavity boundary conditions, i.e., by a geometrically induced birefringence $\Delta n_g$, and are mixed by the Faraday effect.31 One conclusion that was drawn in Ref. 31 was that $\Delta n_g$ quenches the overall Faraday rotation. Minimizing $\Delta n_g$ in turn maximizes the magnetic field sensitivity and so polarization rotation at the output coupler becomes significant. Cavity-enhanced polarimetry32 is an extension of this operational principle through which chiral measurement can be considered.

In this paper, we present a WGM sensing platform that dually incorporates thermal tuning and magneto-optical responsivity. A germanate (56GeO2-31PbO-9Na2O-4Ga2O3) microsphere with a high Verdet constant is fabricated with a central gold conducting wire to modulate the WGM resonance via heating and induce a magnetic field on the order of 1 G. The cavity-wire structure is fashioned by inserting...
a sub-millimeter diameter gold wire into a germanate capillary, then a capillary segment with a wire protrusion is melted inside a ceramic microheater. Convection and surface tension promote the formation of a germanate microspherical profile around the wire (with the cavity radius on the order of hundreds of μm) and glass isotropy is ensured by the germanate’s slower crystallization rate. The wire geometry creates a B-field that is parallel or antiparallel to the WGM propagation direction throughout current reversal in time. Critically, as the cavity refractive index (n_c) profile guides quasi-TE and quasi-TM modes differently, we show that Δn_g decreases with thermal conductance throughout the cavity with the increasing root-mean-square amplitude of the oscillating bias voltage. This WGM tunability scheme excludes large and expensive electromagnets in order to limit the device footprint.

Scans were performed across WGM resonances using a tunable external cavity laser of central wavelength \( \lambda = 642 \text{ nm} \) in the geometry shown in Fig. 1. Light is focused onto the internal surface of a rutile prism, forces acting on the suspended microsphere contacts the prism, forces acting on the microsphere-stem cantilever from capacitance at the soft glass interface and flexion from heating can vary the coupling to the WGM and hence alter the linewidth. The magnetic field oscillation frequency \( f_{\text{M}} \) is not equal to that of the recorded response of Fig. 1(c)—what is instead observed is a WGM perturbation at \( 2f_{\text{M}} \) due to heat conduction that is independent of the current direction. The trace’s noise floor in the tens of fm range, in this case derived from the cavity quality factor \( Q = \lambda_{\text{res}}/\delta \lambda \approx 2 \times 10^7 \), exceeds the laser phase noise.

Further investigation of the perturbed WGM resonance was carried out by frequency domain analysis. The entire resonance trace of Fig. 2(a) was decomposed into its frequency components [Fig. 2(b)], revealing the expected DC component and \( 2f_{\text{M}} \) peaks for a full-wave rectified resonance signal response. These peaks originate from thermal nonlinearities; however, \( f_{\text{M}} \) peaks also exist within the spectrum. Normalized spectral peak amplitude vs frequency curves in Fig. 2(b) for the two separate series of peaks differ in bandwidth, thus indicating separate time constants. The model proposed in Ref. 31 derived from the coupled mode theory contextualizes this disparity: once the B-field is sufficient to overcome the geometrical birefringence Δn_g, mode mixing produces deviations in quasi-TE and quasi-TM WGM eigenfrequencies away from degeneracy. Consequently, a partial-wave rectified resonance shift pattern from a weak intracavity Faraday effect would exhibit the \( f_{\text{M}} \) peak seen in our experiment. With lower Δn_g, coupling between quasi-TE and quasi-TM WGMs is detected at lower magnetic field thresholds.

Faraday rotation \( \theta_F \) is optimized in the unquenched regime (Δn_g = 0) and highly dependent on the magnetic field strength. Calculations in Fig. 3(a) outline that \( \theta_F \) and hence the shift Δλ_{\text{Faraday}} for a tellurite WGM microsphere are linear with the B-field. Simulated fundamental quasi-TE and quasi-TM WGMs with azimuthal mode order \( m = 975 \) (i.e., near the experimental operating wavelength) places the operating points at Δn_g = 0.00146, neglecting the cavity index profile variation from thermo-refractivity and thermal expansion. Accounting for this tuning, on the other hand, can lead to a displacement in the radial position of the guided WGM intensity maxima. Figure 3(b) depicts the experimental resonance trace when increasing the root-mean-square amplitude of the bias voltage. By fixing the duty cycle of the electrical signal, the time-averaged heating of the...
oscillation and close in value (Faraday effect superposition. WGM resonant linewidths are similar in rise toward the peak, in agreement with thermal and intracavity these modes scales linearly with.

Plasmonic nanoantennae from Ref. 6 may be functionalized with birefringence. At a peak-to-peak bias voltage $V_{\text{pp}}$ of and detecting Faraday rotation from single molecules will, however, of enantiomer layers on the cavity surface. Distinguishing the chirality of and detecting magnetic field-dependent protein behavior, such as cryptochrome signaling. Spin states correlated with such biochemical reactions could be manipulated with the local magnetic field and probed according to the magneto-optical coupling of the resonator, i.e., through resolvable discrepancies between the quasi-TE and quasi-TM WGM resonance response.

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REFERENCES


