Faraday Effect in Long Telecom Fibers with Randomly Varying Birefringence

Misha Brodsky
AT&T Labs Research, Middletown, NJ 07748
brodsky@research.att.com

A. A. Sirenko
Department of Physics, NJIT, Newark, NJ 07102

A. Zavriyev, A. Trifonov
MagiQ Technologies, Inc., Somerville, MA 02143

Abstract: We measure relative propagation delay between two orthogonally polarized pulses in long fibers in the presence of a weak axial magnetic field (~50μT). We find that the fiber birefringence modifies the Faraday polarization eigenstates, which became noncircular and wander in time.

OCIS codes: (230.2240) Faraday Effect, (060.5530) Pulse propagation and solitons, (260.3160) Interference

1. Introduction

Recent advances in Quantum Cryptography open feasibility of communication based on cryptographic keys secured by the laws of physics [1]. The major issues impeding deployment of such systems are the loss and decoherence effects in fiber links. The latter arises from both time variation of the optical path lengths and PMD. Compensation of decoherence requires complex and expensive phase-correction feedback schemes. Modern commercially available fiber-based quantum key distribution (QKD) systems employ an elegant bidirectional solution [1,2], in which the light pulses travel back and forth along the same fiber and all optical path and polarization effects in the fiber are self-compensated with a Faraday mirror at one end. This scheme, however, does not compensate for the Faraday effect in the transmission fiber itself, which could be caused, for example, by the weak geomagnetic field (about 50 μT). In fact, we have previously shown that application of a small axial field of this magnitude is sufficient to cause an increase of the quantum bit error rate (QBER) for a commercial QKD system for some input states of polarizations (SOP) [3]. At that time we had not yet explained the QBER performance data.

Here we present a thorough study of the underlying physics of the previous observations. We investigate the Faraday effect in transmission fibers in reflection mode with a Faraday mirror at the end of the fibers – exactly the same configuration as used in commercial QKD systems. The magnetic field B is applied by encasing fiber spools in a torodial solenoid, such that field lines are aligned with the fiber. Utilizing interferometry we were able to measure the miniscule group delay ($\tau \sim 0.2$ fs) between two pulses launched into the 25 km long fiber with orthogonal SOPs. Note, that in the absence of randomly varying birefringence along the fiber this delay would be two orders of magnitude larger [4,5]. For sufficiently small values of the magnetic field the delay τ is found to be linear in B. For a fixed field value, we measure the delay τ as a function of input SOP of the first pulse, as this SOP covers the Poincare Sphere uniformly. We establish the existence of two orthogonal polarization eigenstates $\vec{f}_{1,2}$, corresponding to maximal positive and negative delays: $\pm\tau_{max}$. For arbitrary SOP $\vec{s}$, the time delay τ becomes $\tau = \tau_{\max}(\vec{s} \bullet \vec{f}_1)$. In addition to the time delay, the magnetic field rotates the polarization of the original pulses by the angle $\theta = \theta_{\max}\left|(\vec{s} \times \vec{f})\right|$. The maximal rotation angle θ_{max} and τ_{max} are related by a simple expression $\tau_{\max} = \frac{\lambda n}{c}\frac{\theta_{\max}}{2\pi}$. We prove that the time delay τ is the primary cause of the increasing QBER. Thus, the QBERs are larger for SOPs near the eigenstates. Interestingly, unlike the case of the classical Faraday effect in homogeneous solids, the polarization eigenstates are not necessarily circular. Moreover, we observe that they change in time, as the fiber birefringence configuration is changed by the ambient conditions.

2. Experimental Setup

Fig. 1 depicts a schematic of our setup. A linearly polarized 6ns laser pulse is split by an unbalanced Mach-Zehnder interferometer, the delayed half-pulse SOP is flipped by a λ/2 plate, and thus the resulting two pulses are emitted into the fiber in orthogonal polarizations. On the other end of the fiber they are reflected by a Faraday mirror and

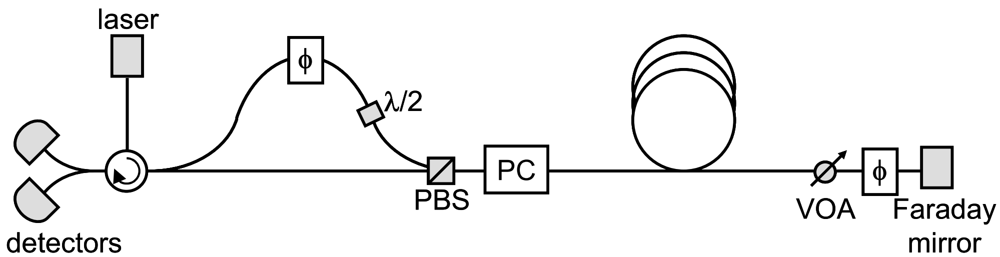

Fig. 1. Experimental Setup schematic

then return to the interferometer with their polarization switched. The polarization beam-splitter makes the leading (trailing) pulse enter the long (short) arm of the interferometer. The original delay is thus cancelled and the two pulses interfere. Additionally, two time gated phase modulators (denoted by ϕ) can adjust the relative phase between two pulses to be either 0, π, or π/2. Depending on the phase bias, the returning light is directed to either one of the detectors (D1, D2), or is split equally between D1 and D2. A polarization controller varies the input polarization into the fiber. To generate the magnetic field we wrapped toroidal coils onto the spool itself and connected them to a current source. The strength of the field was calibrated by a magnetometer. Field-induced relative group delay τ is much smaller than the pulse width and, therefore, can be thought of as just an additional phase difference $\phi = 2\pi \frac{c}{\lambda n}\tau$, which affects the interference between the two pulses.

3. Results

First we show that the applied field B indeed impacts the phase difference ϕ for a fixed SOP. Fig. 2 plots normalized outputs of detectors D1 (solid symbols) and D2 (empty symbols) as they vary with changes in magnetic field between $-4.36B_0$ and $+4.36B_0$ (B_0=$50\mu T$) around three preset phase bias points: 0 (circles), π/2 (triangles), π (squares). An empirical coefficient $k \approx 0.21$ relating the phase and the field strength $\phi = kB / B_0$ is chosen to fit the data to the functions $D_{1,2} = (1 \pm \cos(\phi))/2$ shown in Fig.2 as solid lines. The phase shift of about 0.2 radian for B=B_0 corresponds to a relative group delay of 0.25 fs.

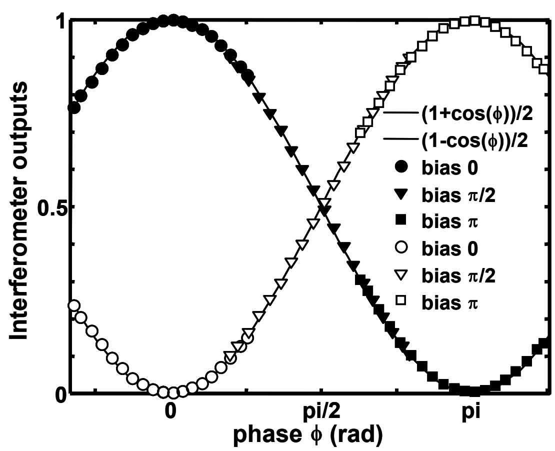

Fig. 2. Interferometer output D1 (●,▼,■), D2 (○,▽,□) as the phase difference between two pulses ϕ is varied by the field B. Phase bias of 0 (●,○), π/2 (▼,▽); π (■,□)

To study the effect as a function of input polarization we set up a phase bias to π/2 and the field to B=$2B_0$. As could be seen from Fig.2 these settings maximize the interferometer sensitivity. As the polarization controller goes through 625 pre-calibrated settings covering the entire Poincare Sphere, the two detector's count D1 and D2 are recorded for each SOP setting. The acquired phase difference between two pulses can the be calculated as $\phi = asin\left(\frac{D1-D2}{D1+D2}\right)$. Fig. 3a represents the phase ϕ on the Poincare sphere as gray colored dots circle, lighter shade corresponding to positive phase. The position of each symbol shows the input SOP of the first pulse. The sphere is

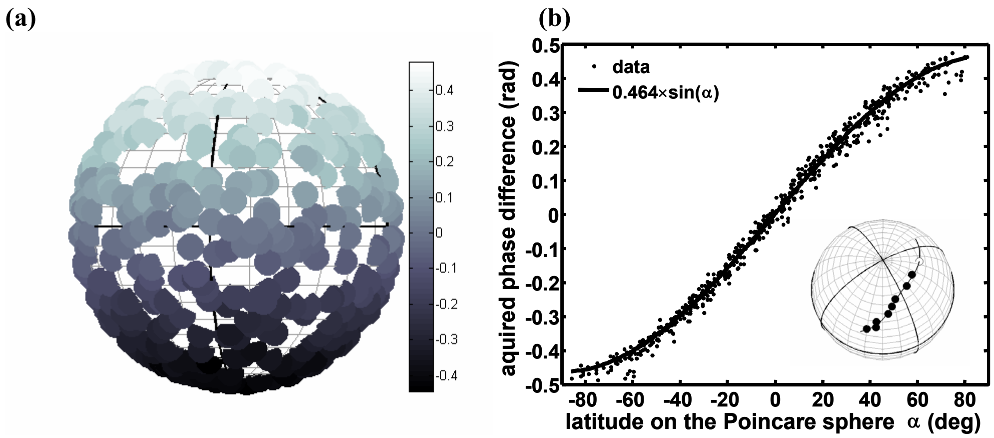

Fig. 3 (a) aquired phase difference ϕ (grayscale) as a function of input SOP (position on the sphere); (b) ϕ as a function of the latirude: experiment (dots), fit (solid line); inset: evolution of the eigentstate f_I in time: data (circles), fit (solid line), the first datapoint shown as a white circle

rotated such that a clearly seen axial symmetry goes along the North-South poles direction. The maximal positive phase (the first pulse is leading the second) is observed for the first eigenstate SOP $\vec{f}_1$ at the North Pole, the maximal negative phase (the first pulse is trailing the second one) occurs for the second eigenstate SOP $\vec{f}_2$ at the South Pole. There is zero phase delay for the polarization states on the equators. Fig. 3b plots the phase ϕ as a function of the latitude α on the sphere. The data are fitted by the function $\phi = 0.464 \times sin(\alpha)$. In other words, the time delay for arbitrary SOP can be expressed as $\tau = \tau_{\max}(\vec{s} \bullet \vec{f}_1)$, where τ_{max}=0.55fs for B=2B_0. This equation is similar to one known in the context of PMD [6,7]. The inset in Fig. 3b shows the time evolution of the eigenstate $\vec{f}_1$ in a three hours period. The data points are shown as circles, and a polynomial fit as a solid line. From this evolution we conclude that the eigenstates are not circular.

Finally, using the same setup for the QKD measurements, we verified that the observed phase delay ϕ causes the QBERs for input SOPs, which are sufficiently close to either one of the $\vec{f}_{1,2}$, and, in fact, the QBER can be expressed in terms of ϕ as $QBER \propto (1-cos(\phi))/(1+cos(\phi))$.

4. Conclusions

We study the net Faraday effect in long fibers with random birefringence. We find that a weak magnetic field of 50μT (comparable to that of the Earth) applied along long fibers could result in a group delay between orthogonally polarized pulses. Our observation shows that the delay scales linearly with a magnetic field and shows a strong dependence on the SOP, similar to that of the classical Faraday effect. Random fiber birefringence seems to reduce the measured group delay but does not eliminate it completely. In addition, time variations of fiber birefringence, causes the Faraday eigenstate to wander in time. The observed effect is important for modern bidirectional QKD systems.

7. References.

1. N.Gisin *et al,* “Quantum Cryptography,” *Rev.Mod.Phys.*, vol.74, p.145, 2002
2. H.Zbinden *et al*, “Interferometry with Faraday mirrors for quantum cryptography,” *Electron.Lett.* vol. 33, p.586, 1997
3. M. Brodsky *et al*, “Effect of a weak magnetic field on quantum cryptography links,”in *Proc. ECOC*, 2005, vol. 6, pp. 19-20
4. J.L. Cruz *et al*, “Faraday effect in standard optical fibers: dispersion of the effective Verdet constant,” *Appl. Optics*, vol.35,p.922, Feb 1996
5. A.H. Rose *et al*, “Verdet Constant Dispersion in Annealed Optical Fiber Current Sensors,” *IEEE J.Lightwave Technol.*,vol.15,p.803, May 1997
6. L. F. Mollenauer, and J. P. Gordon, “Birefringence-mediated timing jitter in soliton transmission,” Optics Lett. vol. 19, 375-377 (1994).
7. L. Nelson, R. Jopson, H. Kogelnik, and J. Gordon, "Measurement of polarization mode dispersion vectors using the polarization-dependent signal delay method," Opt. Express vol. 6, 158-167 (2000); http://www.opticsinfobase.org/abstract.cfm?URI=oe-6-8-158