Effect of a Weak Magnetic Field on Quantum Cryptography Links

M. Brodsky (1), M. Boroditsky (1), M.D.Feuer (1), A. Sirenko (2)
1 : AT&T Labs Research, 200 S. Laurel Avenue, Middletown, NJ 07041
2 : Department of Physics, NJIT, Newark, NJ 07102
brodsky@research.att.com

Abstract *We study the performance of a commercial bidirectional Quantum Key Distribution system in the presence of a weak magnetic field (about 50 µT) applied along the fiber axis. We observe a quadratic increase in quantum bit error rate with the angle of Faraday rotation.*

:

Introduction

Quantum Key Distribution (QKD) exploits the quantum-mechanical properties of light to generate identical pairs of random secret keys for two parties connected by an optical fiber. The entire QKD field surged recently and has already reached its first commercial offerings [1]. While integration of these QKD systems into real networks remains challenging, their range of applicability is of interest to service providers.

Both commercially available systems utilize bidirectional technology [2], in which the key is encoded in a photon phase, and polarization effects in the fiber are selfcompensated with a Faraday mirror at one end. The detailed explanation of such scheme can be found elsewhere [3]. Briefly, two relatively strong pulses are delayed with respect to each other by an unbalanced Mach-Zehnder interferometer at Bob's end, and are emitted in orthogonal polarizations. They then travel to Alice (where they are attenuated to a proper photon count), are reflected by a Faraday mirror to return to Bob with their polarization switched. This ensures that the leading (trailing) returning pulse now enters the long (short) arm of Bob's interferometer and as a result two of them recombine. Depending on the phase delays imposed at Bob's and Alice's ends the recombined photon is directed to one of the two detectors thus producing either "1" or "0". Because of inherent bidirectionality of such scheme, the impairments considered up today are Raman and Rayleigh backscattering [4] or fast (few hundred microseconds) changes in the fiber, which are comparable to the photon's round trip time.

There is, however, yet another subtle but potentially harmful phenomenon which has been largely overlooked up to now – Faraday effect in the transmission fiber itself. When light propagates in fibers installed in North-South directions the weak magnetic field of the Earth (which is about 50µT) induces small circular birefringence in the fiber. It is believed that much stronger linear birefringence in optical fibers quenches the Faraday effect [5].

Contrary to such belief, in this paper we demonstrate that there exists a small but measurable Faraday rotation of few tenth of a radian on three spools of various fiber type ranging between 22 to 26 km in length, which are placed in toroidal magnet, such that field lines are aligned with the fiber. Note that there is no effect when the same spools are placed in uniform field of the same magnitude perpendicular to the spool axis. We further study Faraday rotation in reflection mode with a Faraday mirror at the end of the fibers. We find that this rotation is almost linear in magnetic fields up to 250µT, reverses its sign with reversal of the field, depends on optical frequency and input polarization into the fiber in a fashion similar to PMD. That is, there exists an eigenstate of input state of polarization (SOP), which is not perturbed by the field, and the effect is the strongest for input SOPs, which are 90° away from the eigenstate on the Poincare Sphere. As the Faraday effect *can not* be undone by Alice's Faraday mirror, it therefore affects performance of the tested QKD system by increasing quantum bit error rate (QBER) with applied field. By performing QBER measurements at various input SOPs and in a range of magnetic fields on two fiber spools we determine an empirical quadratic dependence of QBER on Faraday angle, which is *the same* for two fibers measured. We speculate that our measurements can not be solely explained by the small tilt of SOPs of the returning pulses and might arise from changes in the relative phase between the two pulses might need to be taken into account.

Experimental Setup

Our setup is shown in Fig.1. Two parts of a commercial QKD system (Bob and Alice) were connected by a spool of fiber. To generate the magnetic field we wrapped toroidal coils onto the spool itself and connected them to a current source. A polarization controller PC2 between Bob and the spool permits variation of input SOP. QBER were recorded by system's interface. For polarization measurements in magnetic field Bob was disconnected and cw light from a tunable laser source passed through a polarization controller PC1, and then was fed through a 3dB coupler into PC2. A simple Faraday mirror (FM) was attached to the other end of fiber to replace Alice in such a case. A polarimeter picked the reflected signal from another arm of the coupler. As the fibers were slowly drifting during the measurements, we constantly switched between two setups, to correlate QBER and the Faraday rotation angle.

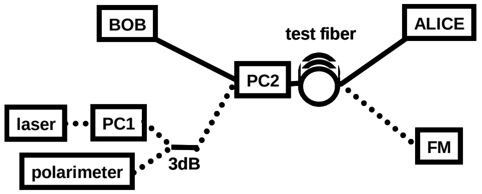

Fig. 1 QKD path(solid); Polarization path(dashed)

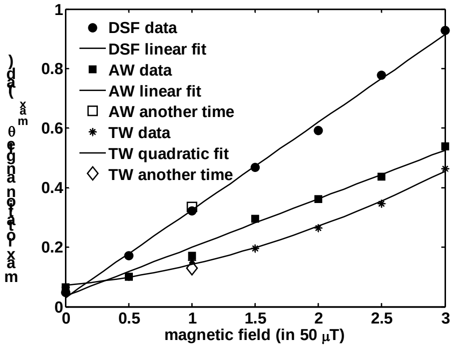

Fig. 2 Faraday rotation vs B for 3 fibers; 1550nm

Results

Fig. 2 shows the maximum angle of Faraday rotation θ_{max} (corresponding the worst launched condition set by PC2) taken at λ=1550nm for three different spools as a function of magnetic field, which is measured in units the Earth magnetic field (B_0=50μT). Filled circles, filled squares and stars correspond to the data for 22.8km DSF (●), 26.4km AllWave (AW) (■), and 25.2km TrueWaveReach (TW) (*) spools. As polarization properties of the AllWave and TrueWave fibers changed in time two more points for these two fibers taken at different time at B= B_0 illustrate a range of this variation. Relatively strong effect in DSF and AW seems linear, while smaller effect in TW is quadratic. The maximum rotation angle θ_{max} also varies with wavelength. The values measured on the three fibers between 1530nm and 1570nm at the field of B=B_0 range between 0.4 rad (for AW at 1540nm) and 0.1 rad (for TW at 1570nm).

To measure QBER we first set the field to a relatively high value (B=2B_0) and then vary PC2 to get a high QBER count. Once the proper SOP in found, QBER is taken for the entire field range. System's interface updates QBER averaged over 10 seconds, and typically we take 6 readings for each point. This gives us a reasonable accuracy of 0.06% but limits the amount of data given temporal drift in fibers. Seven QBER curves are shown in Fig.3 for various SOPs in two different fibers (DSF and AW). Instability of TW fiber together with small values of Faraday rotation at 1550 nm during the time of the measurements prevented us from taking QBER curves on that fiber. The maximal effect for the field value B=B_0 is measured to be 3.65%, while typical QBER for zero field is 1.55% (maximal 1.88%). Thus we conclude that the effect of the Earth's magnetic field is not negligible. Naturally, the effect is bigger in larger fields (or presumably in longer spans).

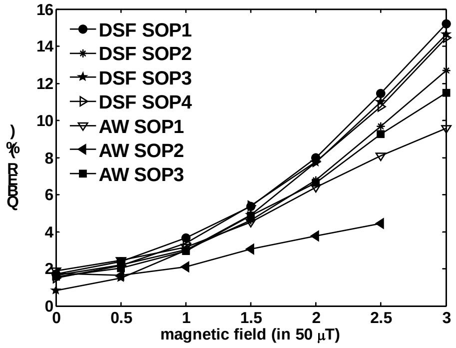

Fig.3 QBER for various input SOP for two fibers

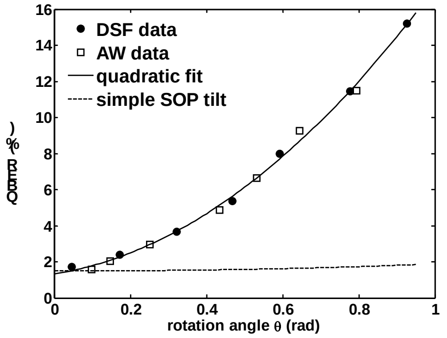

Figure 4. QBER vs θ_{max} for 2 fibers: quadratic fit (solid), QBER due to SOP misalignment alone (dashed)

Since net Faraday rotation is different in different fibers at any given time, we find it instructive to plot the QBER data as a function of maximal rotation angle θ_{max} (Fig.4). From each set of QBER curves, taken on DSF and AW fibers, we pick two the largest, each one corresponding to the worst launched SOP condition achieved in that fiber. Now we plot them together (● for DSF, □ for AW) in Fig. 4 as a function of maximal rotation angle θ_{max} measured during the QBER test (note that due to drifts, θ_{max} for AW fiber is about 1.5 times larger than that shown in Fig.2). The two superimposed data sets lay right on top of each other, and, in fact, could be fitted by the *same* quadratic dependence of the angle: $QBER \approx 10.5 \times \theta_{max}^2 + 5.2 \times \theta_{max} + 1$ shown as solid line in Fig. 4. It is interesting to note that a simple polarization misalignment of pulses returning to Bob will only reduce the photon count by $\cos^2(\theta_{max}/2)$, increasing QBER only slightly (dashed line in Fig. 4). Thus we believe a magnetic field induces some relative phase change between the two pulses.

Conclusions

Utilizing a commercially available QKD system we performed QBER measurement through various spools of fiber subjected to a weak magnetic field. We found that Faraday rotation by such small fields of 50μT (comparable to that of the Earth) could slightly degrade the performance of QKD system. We obtained an empirical dependence of QBER degradation on the maximal angle of Faraday rotation. Our results suggest that the Earth's magnetism could influence QKD links over some installed routes.

References

1. www.idQuantique.com, www.MagiQtech.com
2. H.Zbinden et al, *Electron.Lett.* vol. 33,pp.586, 1997
3. N.Gisin et al, *Rev.Mod.Phys.*, vol.74,pp.145, 2002
4. D.Subacius et al, *Appl.Phys.Lett.*, vol.86, 2005
5. R.H.Stolen et al,*Appl.Opt.*, vol.19, pp.842, 1980