Low magnetic field effect of circular conductors on a fiber-optic transmission system

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Abstract. In a communication system that uses fiber optics, light wave transmissions respond to the influence of surrounding magnetic fields, thereby causing undesirable changes in the output signal. Thus, an important task in electrical engineering is analyzing polarization and intensity changes to protect sensitive data transmission systems from unintended sources of magnetic disturbance. In this study, we propose a signal processing method to evaluate fiber-optic transmission systems under the influence of a weak magnetic field. This method is conducted by performing experimental and theoretical measurements on the axis of light propagation using a laboratory setup and simulation software OptiSystem (version 7.0). Results show that the shape, size, and axial positions of the conductor plays a key role in strengthening the magnetic field influence on increasing the bit error rate and decreasing the Q factor of the communication system.

Keywords: Q- Factor, fiber optics, laser, magnetic field effect, bit error rate.

1. Introduction
The challenge of using optical fibers as a waveguide in data transmission through light reaches the end of the fiber only slightly distorted is an attraction in the presence of external perturbations. An optical fiber is a cylindrical dielectric waveguide made of low-loss material that transmits light depending on the process of total internal reflection. However, low power is lost during each reflection [1]. In a communication system that uses fiber optics, light wave transmissions react to changes in their surroundings in various ways, thereby causing undesirable changes in output signal [2]. Several studies
have been conducted to analyze the polarization and intensity changes generated by external magnetic fields. Studies have been published on the influence of the magnetic field on optical signal propagation direction [3-5], tunable refractive index and field dependent transmission [6], and degree of overlapping of fibers to control the orientated behavior [7]. An assessment of the magnetic field created by the flow of current through cables or any conductor of various configurations is important in electrical engineering to protect sensitive devices from unintended sources of magnetic disturbance [8]. Biot–Savart law for a volume distribution of current was used to obtain a circulation formula for the magnetic field [9].

In this study, we propose a signal processing method to evaluate fiber-optic transmission systems under the influence of a weak magnetic field. Experimental and theoretical measurements are conducted on the axis of light propagation using a laboratory setup and simulation software OptiSystem7.0, Optiwave Systems Inc.

2. Experimental setup and principle

The experimental setup consists of three main elements: an optical source as a data carrier, an optical fiber as a transmission channel, and a magnetic field source. A magnetic field arises due to the motion of charges on a conductor. When charges move in a conducting wire and produce a current I, the magnetic field can be calculated at any point (P) by adding up the magnetic field contributions, \( \vec{d\,B} \), which arise from small parts of wire \( d\,\vec{s} \) due to the current. According to Biot–Savart law, the infinitesimal current source of wire segments can be written as \( I\,d\,\vec{s} \) [10, 11].

\[
d\vec{B} = \frac{\mu_0}{4\pi} \frac{I\,d\,\vec{s}}{r^2} \times \frac{r}{r}
\]

Where \( \mu_0 \) is permeability of free space

\[
\mu_0 = 4\pi \times 10^{-7} \frac{Vs}{Am}
\]

As shown in Figure 1, the position vector from the part of the conductor under consideration to point P is given by \( r \).

![Figure 1. The magnetic field of a current-carrying conductor](image)

The total magnetic field of an infinitely long wire is calculated as follows [10]:

\[
\vec{B} = \frac{\mu_0 \, I}{4\pi} \frac{2}{r}
\]

At a distance \( r \) from the axis, the field lines are concentric around the cylinder axis, as shown in Figure 2.
The subject of magnetic field influence on fiber-optic transmission systems has not been widely studied. In general, fiber optic loss is expressed in decibels (dB) and calculated [12] with the following equation:

$$\text{loss}_{\text{dB}} = 10 \log \frac{P_{\text{out}}}{P_{\text{in}}}$$  \hspace{1cm} (3)

where $P_{\text{in}}$ is the input power to the fiber and $P_{\text{out}}$ is the power at the output of the fiber. As shown in Figure 3, the experimental setup consists of the following: a narrow line-width diode laser (650 nm) that is applied as a light source, a transmission optical fiber, a fiber-optic power meter, high-current power supply equipment, a Tesla meter with axial B-probe, a Hall effect sensor, and an adaptor for conductor loops.

The proposed technique is divided into two procedures. The first procedure consists of the following steps:

- The adapter is mounted and attached to a 40 mm conductor loop.
- The optical fiber is aligned with the B-probe and passed through the center of the conductor loop.
- The B-probe is aligned toward the center of the conductor loop and the conductor loop is aligned with the Hall sensor.
- The light from the laser diode (650 nm) is launched and transmitted through the optical fiber and then enter into an optical power meter.
- The magnetic field is controlled by increasing the current (I) from 0 to 20 ampere in intervals of 2 ampere. The measured values of the magnetic field (B) and optical output power are recorded.
- The 40 mm conductor loop is replaced with 80 mm and 120 mm conductor loops. In both cases, the magnetic field is measured. The optical output power and measured values are recorded.

The second procedure is performed by repeating the measurements after placing the optical fiber near but out of the conductor loop.

**Figure 2.** The magnetic field of an infinitely long wire.
3. Design and simulations of Propagation setup

Numerical simulations are necessary to investigate the actual performance of data transmission systems under the influence of weak magnetic fields. This task is usually conducted by including the effect of external perturbations on the system performance. The full design of a fiber optic transmission system is presented in Figure 4. The data generated by the pseudo-random bit generator are encoded through a non-return-to-zero pulse generator, and light is modulated by using a Mach–Zehnder modulator. Thus, the CW laser source (1500 nm) acts as the carrier source. The laser passes through the optical fiber channel with a length of 1 km to supply a channel capacity of approximately 30 dBm. The output optical signals are received by an Avalanche photodetector. This simulation uses three visualizers: an optical power meter to measure the power received in dBm and watts, an electrical carrier analyzer, and a BER analyzer to calculate the bit error rate (BER) value and Q factor. For good signal reception, the minimum Q factor is 6 and the BER value is $10^{-9}$ [13]. The design parameters used in the numerical simulation are shown in Table 1.

![Figure 3. The experimental setup](image-url)
Table 1. Fiber optic system design specifications used in simulation.

| Parameter                     | Value   |
|-------------------------------|---------|
| wavelength                   | 1550 (nm) |
| Transmitter optical power    | 30 (dBm) |
| Transmitter divergence angle | 2 (mrad) |
| Receiver sensitivity         | -20 (dBm) |
| Transmitter aperture         | 2 (cm)  |
| Receiver aperture            | 10 (cm) |
| Transmitter efficiency       | 0.5     |
| Receiver efficiency          | 0.5     |

4. Results and discussion

In the experimental part, the performance of the optical fiber as a waveguide exposed to an external magnetic field was evaluated. Measurement data were collected continuously 10 times for the magnetic field B of a circular conductor loop as a function of the current I. Furthermore, the optical power fluctuation from the fiber as a result of beam propagation through (inside) and near (outside) the circular conductor loop were measured and recorded. Using these data, we determined the magnetic field rate, power fluctuation rate, and power fluctuation percentages of the three circular conductor loops (40, 80, and 120 mm), as shown in Table 2.
Table 2. Experimental measurements

| Conductor loop diameter (mm) | Magnetic field rate (mT) | Power fluctuation rate (mW) | Power fluctuation percentage (%) |
|-----------------------------|--------------------------|----------------------------|----------------------------------|
|                             | Inside the loop          | Outside the loop           | Inside the loop                 | Outside the loop               |
|                             | Inside the loop          | Outside the loop           | Inside the loop                 | Outside the loop               |
|                             | Inside the loop          | Outside the loop           | Inside the loop                 | Outside the loop               |
|                             | Inside the loop          | Outside the loop           | Inside the loop                 | Outside the loop               |
| 40                          | 0.4                      | 0.388                      | 0.5785                          | 0.570                          | 115.7                          | 114                          |
| 80                          | 0.239                    | 0.215                      | 0.4938                          | 0.4777                         | 98.8                          | 95.6                          |
| 120                         | 0.203                    | 0.156                      | 0.4924                          | 0.4757                         | 98.5                          | 95.1                          |

Furthermore, we conducted the simulations and numerical calculations to quantify the efficiency of fiber-optic transmission systems under the influence of a weak magnetic field. Percentages of experimentally measured power fluctuation, as reported in Table 2, were used to predict the power fluctuation for the proposed system, as shown in Table 3.

Table 3. Power fluctuation percentages of 1550 nm fiber optic system.

| Conductor loop diameter (mm) | Power fluctuation Percentages (dBm) | BER *E-11 |
|-----------------------------|------------------------------------|-----------|
|                             | Inside the loop                    | Outside the loop | Inside the loop | Outside the loop |
| 40                          | 34.7                               | 34.2          | 1.2373          | 1.2372          |
| 80                          | 29.64                              | 28.68         | 1.2366          | 1.2364          |
| 120                         | 29.55                              | 28.5          | 1.2363          | 1.2364          |

Considering the data in Table 2, we can conclude that the external magnetic field has a significant effect on the stability of the output power in both optical paths (inside and outside) the loop. These optical paths exhibited a linear response to magnetic field increments. The highest sensitivities were obtained at the center of the conductor loops. The optical fiber showed increased losses in receiving power when the loop diameter around the fiber increased linearly, as shown in Tables 2 and 3. Figure 5 shows a reduction in the Q factor when the loop diameter increases. The results also illustrate that all values of the Q factor are above 6; thus, the light reaches the end of the fiber with only a slight distortion in accordance with previous findings [14].
5. Conclusion
In this study, the efficiency of the fiber-optic transmission system under the influence of a weak magnetic field was investigated. The results demonstrated that the shape, size, and axial positions of the conductor played a key role in strengthening the magnetic field influence to stabilize the output power, increase the bit error rate, and decrease the Q factor of the communication system. Sensitivities to the magnetic field were determined in both optical paths (inside and outside) the loop. The results also illustrated that all values of the Q factor were above 6, thereby demonstrating that the light reaches the end of the fiber with only slight distortion.

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Figure 5. Conductor loop diameter vs Q-factor
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