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Polarimetric Current Sensor Using an In-Line Faraday Rotator

Fabien BRIFFOD[†a)], **Luc THÉVENAZ**[†], **Pierre-Alain NICATI**[††], **Alain KÜNG**[†††], *and* **Philippe A. ROBERT**[†], ***Nonmembers***

SUMMARY A novel polarimetric fiber optics current sensor configuration using an in-line 22.5 degree Faraday rotator is proposed on this paper. The introduction of the 22.5 degree Faraday rotator allows to obtain a sensor configuration that does not require adjustment on most optical elements, resulting in an accuracy immune to manufacturing issues. Two prototypes are presented in this paper that are designed to measure AC current, yielding in an excellent accuracy over more than 3 decades.

key words: *fiber optic, current sensor, Faraday rotator, polarimetric sensor*

1. Introduction

Fiber optics current sensors offer some advantages compared to the classical current transformer. The intrinsic insulation of the optical fiber is a key feature for high voltage installations. In addition they offer a total immunity to stray magnetic fields and show a wide bandwidth making the observations of harmonics and transients possible.

Producing commercial optical current sensors is still challenging and prototypes are being developed mainly in three different flavors: bulk, fiber interferometric and fiber polarimetric sensors. Bulk current sensors [1] are realized using high Verdet's constant crystals, resulting in an excellent sensitivity, but are subject to alignment and temperature drifts. Optical fibers show a lower Verdet's constant, but winding many turns of the fiber around the conductor results in an improved sensitivity. A general drawback of fiber sensors is that they all suffer from a reduced sensitivity in presence of residual fiber birefringence. The interferometric configuration using a Sagnac interferometer [2] measures the non-reciprocal phase shift with a high accuracy, but the main reported problem is the high sensitivity to mechanical vibrations. The polarimetric method measures the rotation of a linear polarization [3], [4], but such sensors require a precise orientation of the analyzer.

A novel sensor configuration is reported here that solves these problems to a wide extent. The key advantages of this simple and in many senses effective configuration is to require no adjustment at all of the optical elements and its accuracy is very tolerant on their actual value. These features may be decisive to obtain a robust sensor.

2. Description of New Sensor Configuration

This sensor is based on a polarimetric configuration where an in-line 22.5 degree Faraday rotator (or $22.5 + n \cdot 45$ degree rotator) is introduced, as shown in Fig. 1. Two different configurations are presented. Configuration A contains a standard mirror at the far end of the sensing fiber. Configuration B is an improved configuration where the standard mirror is replaced by a Faraday Rotation Mirror. The improvement of configuration B will be explained latter.

The optical configuration is simple and based on the back-and-forth propagation through all successive optical elements, the position of reciprocal and non-reciprocal elements being crucial. Let first assume no electrical current in the conductor. The light is linearly polarized by the polarizer and experiences a 22.5 degree rotation through the Faraday rotator. The sensing fiber is mechanically twisted and is thus predominantly circularly birefringent [5], so that the light polarization remains linear while propagating through the sensing fiber, though experiencing a reciprocal rotation. The light is reflected back by the mirror and, at the Faraday rotator input on the way back, the polarization has the same orientation as in the forward propagation (configuration A). After the additional 22.5 degree rotation, the polarization is oriented at 45 degree with respect to the polarizer axis.

The linear polarization is therefore just set at the half-transmitting point of the polarizer according to the well-known squared cosine law, so that any small rotation of the polarization—like that caused by an electrical current—results in a linear variation of the transmitted intensity as shown in Fig. 2.

An electrical current I_{el} produces a magnetic field that rotates the linear polarization by a angle φ proportional to the integral of the magnetic field $\vec{H}$ along

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[†] The authors are with EPFL Swiss Federal Institute of Technology, Laboratory of Metrology, CH-1015 Lausanne, Switzerland.

[††] The author is with Teletronic SA, CH-2300 La Chaux-de-Fonds, Switzerland.

[†††] The author is with A-One, Optical Networking Group, Bell Labs, Lucent Technologies, Holmdel, NJ 07733 USA.

a) E-mail: fabien.briffod@epfl.ch

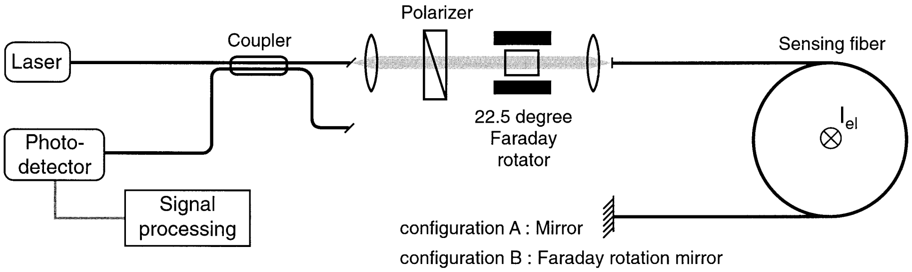

Fig. 1 Schematic diagram of the polarimetric current sensor using an in-line 22.5 degree Faraday rotator.

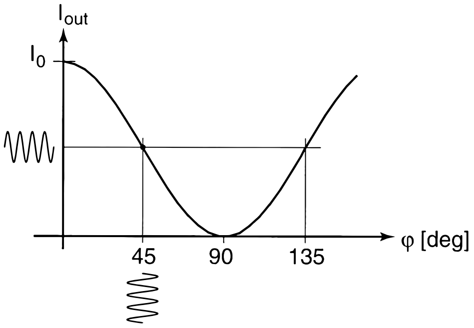

Fig. 2 Polarizer response.

the fiber:

$$\varphi = V \int_l \vec{H} \cdot d\vec{l} \tag{1}$$

where V is the Verdet's constant. The Faraday rotation due to the electrical current is, after a back-and-forth propagation through the sensing fiber:

$$\varphi(t) = 2NVI_{el}(t) \tag{2}$$

where N is the number of turns of fiber around the conductor. The total rotation experienced by the linearly polarized light, including the 22.5 degree Faraday rotator effect, is equal to $\varphi_{tot} = \pi/4 + \varphi(t)$. We consider any reciprocal rotation to be canceled by the back-and-forth propagation. The output intensity then reads:

$$\begin{aligned} I(t) &= I_0 \cos^2(\varphi_{tot}(t)) = \frac{I_0}{2} + \frac{I_0}{2}\cos(2\varphi_{tot}(t)) \\ &= \frac{I_0}{2} - \frac{I_0}{2}\sin(4NVI_{el}(t)) \end{aligned} \tag{3}$$

The sensor is thus set to the optimal operating point for sensitivity and linearity. This sensor being preferably designed for AC current measurement, it is possible to filter the DC and AC components:

$$I_{DC} = I_0/2 \tag{4}$$

$$I_{AC} = -\frac{I_0}{2}\sin(4NVI_{el}(t)) \tag{5}$$

so that normalization of the AC value by the DC value makes it independent from fluctuations of the light intensity and from any kind of optical losses. Finally, we simply obtain:

$$\begin{aligned} I_{el}(t) &= -\frac{1}{4NV}\arcsin\left(\frac{I_{AC}(t)}{I_{DC}}\right) \\ &\approx -\frac{1}{4NV}\frac{I_{AC}(t)}{I_{DC}} \quad \text{for } I_{AC}(t) \ll I_{DC} \end{aligned} \tag{6}$$

The resulting response is approximately linear for low current. But at high current this response becomes nonlinear and can be conveniently approximated using a 3rd order polynomial, resulting in a quicker computation than with the arcsine function. Hence, if the Faraday rotator does not show exactly a 22.5 degree rotation, the operating point is shifted off the center of the linear response, increasing even slightly more the nonlinearity. Thus a calibration of the sensor using this 3rd order polynomial transfer function is required and corrects all possible nonlinearities. The use of a close-to-ideal rotator actually causes a minor penalty and does not decrease the accuracy. It is to notice that in any cases the sensor response remains independent from variation of intensity and losses.

However, the key advantage of this configuration is that neither the polarizer nor the Faraday rotator needs to be oriented, which makes the sensor easy to manufacture and intrinsically stable.

It is moreover possible to substitute the standard mirror by a Faraday Rotation Mirror (FRM) [6], [7] to make the system much more immune to a possible residual birefringence, at the expense of a less cost-effective setup (configuration B in Fig. 1). The sensing fiber is never strictly free of birefringence, so that the use of a FRM cancels the effect of this birefringence and its variations. In absence of electrical current the polarization of the backward propagating light is, at any point, orthogonal to the polarization of the light traveling in the forward direction. For instance if a lightwave travels along the fast axis of a birefringent fiber in the forward direction, it travels along the slow axis in the backward direction, making the effect of any birefringence canceled. This particular case can be generalized to any state of polarization by the usual expansion on the eigenaxes of the fiber birefringence.

An immediate effect of the FRM is to shift the operating point from 45 degree to 135 degree. Actually this only changes the sign of the scaling factor.

If the FRM does not show the ideal total rotation of 90 degree, the compensation of the birefringence is no longer perfect and small fluctuations are observed. The operating point is in addition biased but, as mentioned above, this does not reduce the sensor accuracy if a calibration is performed.

When an electrical current is applied, the additional non-reciprocal rotation remains small, so that the birefringence remains compensated to a wide extent, at least to first order. Very large currents cause Faraday rotations of tens of degree. The small residual birefringence is then overshadowed by the large optical activity.

3. Experiments

The light has to be maintained linearly polarized along the sensing fiber and several solutions have been proposed so far to reduce the effect of the linear birefringence present in the sensing head. An annealing process [8] can be used to release the residual or induced birefringence in the sensing fiber. This process has proved its effectiveness but the resulting fiber gets fragile, can thus no longer be manipulated and any recoating of the fiber turns out to reinduce birefringence. In the configuration reported here, a mechanical twist of the fiber was efficiently used to induce an important reciprocal optical activity, so that the effect of birefringence is made negligible and a linear polarization could be maintained [6]. This process turned out to be easier to implement than annealing. A mechanical twist rate of 20 turns/m used on a 135 mm sensing head diameter allows the polarization to be maintained over 20 meters with a equivalent crosstalk of −30 dB.

A 1311 nm multimode laser was used as light source. At this wavelength the rotation angle of the in-line Faraday rotator is equal to 22.0 degree, that is not exactly ideal. The coupler splitting ratio is 50/50 and the polarizer has an extinction ratio of 30 dB. The sensing fiber is made out of 45 turns of mechanically-twisted fiber and a Faraday rotation mirror with a 1302 nm nominal wavelength is placed at the far end. The bandwidth of the sensor has been set at 600 Hz in order to observe harmonics and transients.

4. Results and Discussion

Figure 3 represents a measurement showing the unprocessed optical-electrical transfer function. The noise level is approximately 700 mA, mainly caused by the unstable injection on the first experimental setup and by the interference caused by reflections on interfaces. The rotation of the linear polarization due to a 2 kA electrical current is equal to 10 degree. Our current supply could not deliver more than 2 kA, but current up to 4 kA could be measured as well.

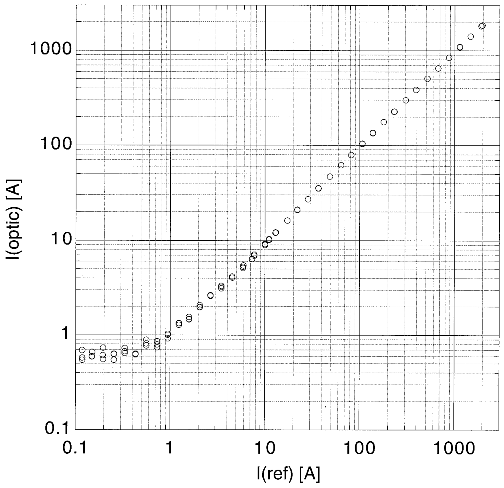

Fig. 3 Sensor optical-electrical transfer function, showing the noise floor level and the possibility to measure over more than 3 decades.

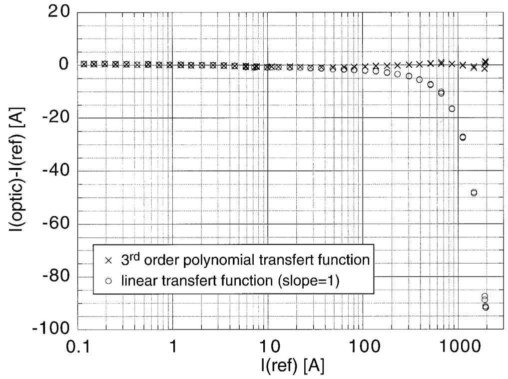

Fig. 4 Difference between the optically measured current and the reference current using a linear transfer function and a 3rd order polynomial transfer function correcting the nonlinear sensor response at high current.

Figure 4 shows the difference between the optically measured current and the reference current, showing that the response is nonlinear for high current, as expected by the theory (Eq. (6)). This figure shows that for a good accuracy over high current, a 3rd order polynomial transfer function should be used. The effect of this linearisation was observed to be similar to the exact arcsine transfer function over this current range.

A variation of the operating point directly results in a variation of the scaling factor. Resulting from Eqs. (3) and (6), the variation of the scale factor as a function of the shift of the operating point is equal to 3.5%/deg. The rotation through the different Faraday elements (the Faraday Rotator and the FRM made of YIG crystals) has therefore to be stable to grant a steady operating point and consequently a constant scaling factor. A rotation variation of −0.04 deg/K was

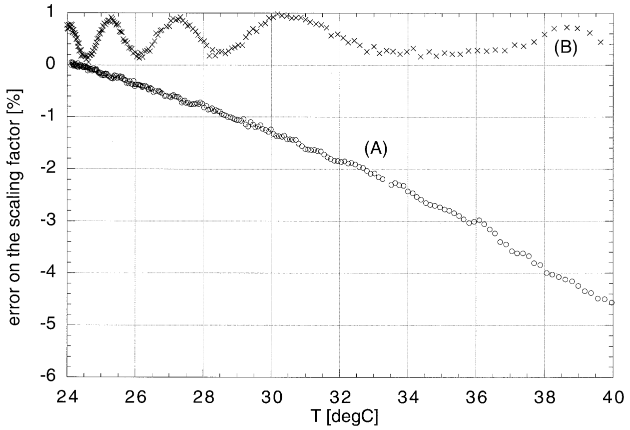

Fig. 5 Error measurement on the scaling factor versus temperature on the sensing fiber in two configurations of the far end mirrors: (A) standard mirror, (B) FRM, but preceded by 1 meter of highly birefringent (HiBi) fiber to demonstrate its efficiency.

measured in the FRM used in the experiment, resulting in a scaling factor drift of 0.14%/K. This means that for highly precise measurements the temperature of these elements has to be stabilized.

A decrease of the scale factor is observed when the polarization is no longer perfectly linear on the polarizer after the back-and-forth propagation through the sensing fiber. The ideal linear polarization of the light is slowly getting elliptical while propagating through the fiber owing to its residual birefringence.

A measurement of the stability of the system is presented in Fig. 5 that demonstrates the improvement resulting from the configuration B using the FRM. When using a standard mirror the light is subjected on the way back to this same birefringence that causes a cumulative variation of the polarization. The temperature-dependent phase delay between orthogonal polarization states makes the ellipticity of the polarization to vary with temperature, resulting in a gradual change of the scaling factor, as shown in Fig. 5(A). The use of the FRM makes the compensation of the birefringence possible on the way back, as explained in the previous section, and consequently to grant a much better stability of the polarization and of the scale factor, accordingly.

In order to demonstrate the efficiency of the birefringence compensation due to the FRM, the measurement B on Fig. 5 was performed with 1 meter of HiBi fiber inserted before the FRM, as shown in Fig. 6, so that the influence of the temperature is greatly enhanced. Even with this 1 meter HiBi fiber, the amplitude of the variations on the scaling factor remain much smaller than when using the standard mirror configuration, as shown in Fig. 5. The observed ripple results from imperfections in the FRM itself, that are mainly due to a small linear birefringence in the FRM crystal. A numerical simulation has shown that such fluctuations may result from a 2 degree residual linear birefringence in the crystal.

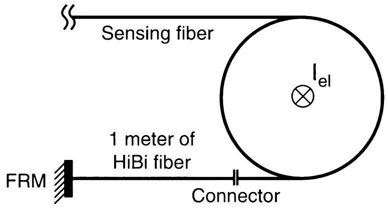

Fig. 6 A 1 meter of HiBi fiber is inserted between the FRM and the sensing fiber coil to demonstrate the efficiency of configuration B.

5. Conclusion

This sensor offers some unique improvements: first it is a self-stable configuration and no optical adjustment is required, resulting in an accuracy immune to manufacturing issues. Secondly, the use of a non-ideal Faraday rotator and mirror does not significantly reduce the sensor accuracy. Finally, this configuration compensates the possible residual linear birefringence in the sensing fiber and the temperature variation of the fiber circular birefringence. Hence this configuration is also greatly immune to vibrations.

Our experimental setup allows measuring AC current with an excellent accuracy over more than 3 decades, with a dynamic range of approximately 4 kA and a noise of approximately 700 mA. The actual accuracy limitations of this configuration come from the uncompensated birefringence in the FRM itself and the variation of the rotation of the Faraday elements with temperature that causes a variation of the operating point.

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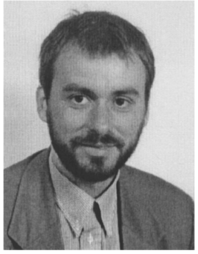
Fabien Briffod received the M.S. degree in electrical engineering from the Swiss Federal Institute of Technology of Lausanne (EPFL), Switzerland, in 1996. He then joined the Metrology Laboratory of the EPFL, where he is currently working towards the Ph.D. degree. His primary research is on fiber optics current sensors.



Luc Thévenaz received the B.Sc. degree in astrophysics from the Observatory of Geneva, Switzerland, in 1982 and the Ph.D. degree in physics from the University of Geneva, Switzerland, in 1988. In 1983, he joined the Group of Applied Physics at the University of Geneva, where he has been engaged in research work on single-mode fiber measurement techniques. In 1988, he joined the Laboratory of Metrology of the Swiss Federal Institute of Technology of Lausanne (EPFL), Switzerland, where he is currently Senior Lecturer. He manages many research projects dealing with guided-wave measurement techniques, Brillouin-scattering optical fiber sensors, nonlinearities in fibers, and spectroscopic techniques. In 1991, he visited the University of Rio de Janeiro, Brazil, and Stanford University, Stanford, CA, where he participated in the development of a Brillouin laser fiber gyroscope. In 1998–1999 he was Research Manager for chemical sensing projects in the company Orbisphere Laboratories in Neuchatel, Switzerland, and also visited the Korean Advanced Institute of Science and Technology in Taejon, South Korea, to develop different fiber laser sensors.

Pierre-Alain Nicati His biography is not available.

Alain Küng received the degree in microtechnology engineering from the Swiss Federal Institute of Technology of Lausanne (EPFL), Switzerland, in 1992, and the Ph.D. degree in electrical engineering in 1997 from EPFL. From 1992 to 1997, he has been with the Metrology Laboratory of the EPFL, where he worked towards his Ph.D. degree on Brillouin fiber laser for which he performed modeling and developed new applications. In 1997–1999, he occupied a postdoctoral position in the Metrology Laboratory of the EPFL, where he dealt with optical telecommunication networks and integrated optics on silicon substrate. His research interests also include characterization of integrated optical devices, fiber sensors and their optical signal processing. He is currently with Lucent Technology in Holmdel, NJ, working on optical amplifiers.

Philippe A. Robert received the Diploma degree in physics engineering in 1961 and the Ph.D. degree in 1968 from the Swiss Federal Institute of Technology of Lausanne (EPFL), Switzerland. From 1968 to 1974, he was with Les Câbleries et Trébleries de Cossonay, where his research interests are in new products and new manufacturing processes, including optical fibers. From 1974 to 1979, he has been engaged in the development and installation of the first optical cables made in Switzerland. Since 1979, he has been a Professor at the EPFL and Head of the Laboratory of Metrology. His current research activities concern guided optics, optical fibers, and integrated optics with applications in optical signal processing, sensors, and telecommunications.