A Novel All-Fiber Configuration for a Flexible Polarimetric Current Sensor

D. Alasia, L. Thévenaz
EPFL, Swiss federal Institute of Technology, Metrology and Photonics Lab
CH-1015 Lausanne, Switzerland
Tel: (++41 21) 693 69 02, Fax: (++41 21) 693 26 14, E-mail: dario.alasia@epfl.ch

Abstract – **This set-up is particularly simple and makes possible the use of a flexible cable that may be plugged to the instrument using connectors for easy field applications. Measurements of AC and DC currents are demonstrated.**

I. Introduction

Fiber-optics current sensors offer many advantages compared to the classical current transformers. The small sizes of optical fibers facilitate the installation of this kind of sensors and the intrinsic insulation due to their dielectric nature represents a significant improvement for high voltage installations. Furthermore, they show a high bandwidth making the observation of harmonics and transients possible and offering a large immunity to stray magnetic fields. Finally, their sensitivity and the absence of saturation of the magneto-optic effect make possible to measure high currents (up to 500kA) [1] as easily as low currents (some amperes).

Producing commercial optical current sensors is still challenging and prototypes are developed basing on three different schemes: bulk-optics, fiber-interferometric and fiber-polarimetric sensors. Bulk-current sensors [2] are made 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 increasing the number of turns of fiber wound around the conductor results in an improved sensitivity. The interferometric-configuration, using a Sagnac interferometer [3], measures the non-reciprocal phase shift with a high accuracy, but the main reported problem is the high vibration sensitivity. The polarimetric method simply measures the rotation of a linear polarization [4] but such sensors require a precise orientation of the analyzer.

As a general feature, all fiber sensors are sensitive to the variations of the sensing fiber birefringence which is responsible for changing the polarisation along the fiber. Many solutions have been proposed to compensate the effect of birefringence, either optically or through a proper signal processing [3][5]. But these techniques are limited to homogeneous linear birefringence along the sensing fiber, so that they turn out to be widely inapplicable in actual conditions in which the fiber birefringence is basically random.

Fortunately the detrimental effect of polarisation mode dispersion in telecommunication systems has led to a big effort for manufacturing very low birefringence fibers at low cost. The remaining birefringence of such fibers turns out to be still too large for the proper operation of a current sensor, but it can now be widely rendered negligible by annealing [6] or mechanically twisting [7], so that a circular or freely-rotating linear polarisation is maintained over the entire fiber length.

An original polarimetric configuration using an in-line Faraday rotator is reported in [8]. This sensor has the key advantage to require no adjustment of any kind on optical elements and its accuracy is poorly dependent on the optical elements tolerance (an extensive study may be found in [9]). However, this advantage vanishes as soon as any polarization-transforming element is inserted after the Faraday rotator, in particular connectors. These practical problems occur when leaving the laboratory experiment to contemplate an industrial prototype of the sensor. In particular, the use of polarisation controllers is needed to grant a perfect linear polarization along the sensing fiber. But, as the main asset of this sensor consists in the total absence of adjustment the concept of an in-line rotator makes no longer sense and the configuration has been transformed to result in a novel *all-fiber* polarimetric configuration, which is presented in this paper.

II. Sensor description

The optical configuration is quite simple and based on a back-and-forth propagation through the sensing head, as shown in Fig. 1. The light generated from a super luminescent diode (SLD) is linearly polarised by traveling through a polarising fiber. Assuming that the electrical current is zero, the polarisation controller PC1 is adjusted in order to compensate the birefringence due to connectors and to have a linear polarisation at the entry of the sensing head. The sensing fiber is mechanically twisted and is thus predominantly circularly birefringent [7]; in this way, light is kept linearly polarised while propagating through it. The light is then reflected back by the Faraday rotation mirror (FRM) and remains linearly polarized, nevertheless *orthogonal* to the incident wave.

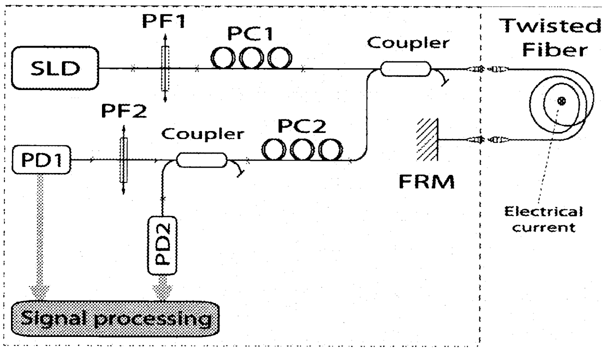

Fig. 1. Schematic diagram of the all-fiber polarimetric current sensor. Fiber polariser PF1 polarises light generated from a super luminescent diode (SLD). Polarisation controller PC1 is set to make the polarisation in the sensing head linear. The twisted fiber maintains the polarisation up to the Faraday mirror. Reflected light is coupled towards PC2 which is set to yield a linear polarisation rotated by 45° at the entry of the fiber polariser PF2. The outgoing light is collected by photo detector PD1. PD2 measures the total intensity of light (I_0).

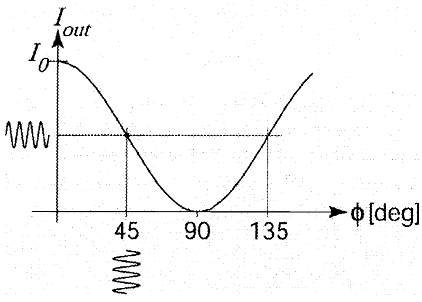

Fig. 2 Polariser response. Transmitted light intensity versus polariser orientation.

On the way back, the coupler redirects light towards the second polarisation controller PC2, which is intended to set the polarisation at 45 degrees with respect to the polariser axis (PF2).

The linear polarisation is therefore just set at the half-transmitting point of the polariser, so that any small rotation of the polarisation – like that caused by an electrical current – results in a linear variation of the transmitted intensity (as depicted in Fig. 2).

When an AC current circulates in a conductor enclosed within the sensing fiber, the linearly polarized light experiences a rotation due to the non-reciprocal Faraday effect. Adopting the signal processing described in [8], the electrical current is directly calculated from AC and DC components of the output intensity:

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

(N being the number of turns of fiber enclosing the conductor and V the Verdet's constant).

If the operating point is slightly shifted off the center of the linear polarizer response, the current response becomes partially non-linear and can be conveniently approximated by a 3rd. order polynomial, with no actual penalty.

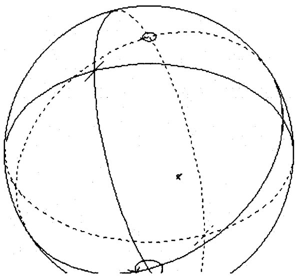

Fig. 3 Polarisation state stability of the backward propagating light after appreciable changes of the sensing fiber geometry.

III. SENSING HEAD FLEXIBILITY

To make the system even more immune to a possible residual birefringence, a Faraday rotation mirror (FRM) is used instead of a standard mirror.

The sensing fiber is never strictly free of birefringence – even after significant twisting – so that the use of a FRM cancels to a wide extent the effect of any residual birefringence and its variations. In absence of an electrical current the polarization of the backward propagating light is, at any point, orthogonal to the polarization of the light travelling in the forward direction, making the effect of any birefringence cancelled [10]. This particular case can be generalized to any state of polarization by the usual expansion on the eigenaxes of the fiber birefringence.

In this way, it is possible to dispose of a very *flexible* sensing cable which is adaptable to a great number of different installations and sensing requirements, and moreover is vibration insensitive (Fig. 3).

IV. POLARIZATION CONTROLLERS ADJUSTMENT

A. Adjustment of controller PC1

The correct adjustment of the polarisation controllers represents the most delicate procedure required by this experimental configuration.

The first polarisation controller (PC1) is set observing the polarisation state of the forward propagating light at the output of the sensing fiber on a polarisation analyzer. Because of the birefringence due to connectors we do not really know what does represent the state described by a point on the Poincaré sphere. We thus need to operate an indirect measure in order to establish whether the propagating polarisation state is linear or not.

A simple technique consists in significantly changing the optical path length of the sensing fiber by modifying its geometry. Since the eigenstates associated with a twisted fiber are left- or right-circular polarisation states, a variation of the birefringence delay do not affect the propagation of circularly polarised light. This means that a point representing a circular polarisation state will be stationary on the Poincaré sphere, while moving the sensing cable.

On the contrary, as a linear polarisation state is very sensitive even to a minor change of the birefringence

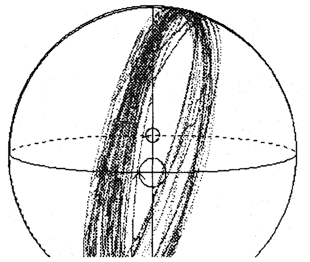

Fig. 4 An appreciable variation of the sensing fiber geometry forces the point representing a linear polarisation state to draw a full circle on the Poincaré sphere.

delay, a point representing it on the Poincaré sphere will draw a full circle (Fig. 4).

B. Adjustment of controller PC2

An efficient method to set the second polarisation controller (PC2) consists in maximizing the AC component of the output light intensity with a non-zero reference electrical current enclosed within the sensing head.

The polarizer response (PF2) to a general (elliptical) polarization state is given by:

$$I = I_0\left(\cos^2\phi\cos^2\varepsilon + \sin^2\phi\sin^2\varepsilon\right) \qquad (2)$$

where ϕ and ε represent respectively the polarization orientation and the ellipticity angle.

The sensitivity to small variations of orientation is simply the derivative with respect to ϕ:

$$\frac{dI}{d\phi} = -I_0\sin 2\phi\cos 2\varepsilon \qquad (3)$$

It is evident that the AC output signal will be maximized only if the sensitivity (3) is maximized:

$$\max\frac{dI}{d\phi} \longleftrightarrow \phi = \frac{\pi}{4}, \varepsilon = 0 \qquad (4)$$

This implies that maximizing the AC component comes to have a linear polarization and to set the working point exactly at 45 degrees.

V. MODELING

A correct adjustment of the polarization controllers may result in a quite delicate and critical operation (especially for controller PC2). For this reason, the development of a proper signal processing, capable of taking into account the non-idealities present in the system, would be a clear advantage.

We suppose now that the lightwave is not perfectly linearly polarized ($\varepsilon \neq 0$) and that the working point is not exactly set ($\phi_0 \neq 45°$). Since the Faraday rotation due to an electrical current is given by $\phi_F(t) = NVI_{el}(t)$, the equation (2) is thus modified:

$$I = \frac{I_0}{2}\left[1 + \cos 2\varepsilon\cos\left(2\phi_0 + 4\phi_F(t)\right)\right] \qquad (5)$$

The AC and DC components of the output intensity may be calculated analytically (using the Jacobi-Anger expansions of trigonometric functions into series of Bessel functions):

$$I_{dc} = \frac{I_0}{2}\left[1 + \cos 2\varepsilon\cos 2\varphi_0 J_0(4\hat{\phi}_F)\right] \qquad (6)$$

$$I_{ac}^{rms} = \cos 2\varepsilon\frac{I_0}{2}\sqrt{\frac{1}{2} + \frac{1}{2}\cos 4\varphi_0 J_0(8\hat{\phi}_F) - \cos^2 2\varphi_0 J_0^2(4\hat{\phi}_F)}$$

It is now possible to solve equations (6) with respect to the ellipticity angle and the working point. We obtain:

$$X_\phi = \frac{\chi\sqrt{1 - J_0(8\hat{\phi}_F)}}{\sqrt{8I_{ac}^2 J_0^2(4\hat{\phi}_F) + 2\chi^2\left[J_0^2(4\hat{\phi}_F) - J_0(8\hat{\phi}_F)\right]}} \qquad (7)$$

$$X_\varepsilon = \frac{\chi}{X_\phi I_0 J_0(4\hat{\phi}_F)}$$

where $X_\phi = \cos 2\phi$, $X_\varepsilon = \cos 2\varepsilon$ and $\chi = 2I_{dc} - I_0$.

I_0 represents the total intensity of light just before the polarizer and is measured by a second photo detector (PD2). The gains of the two photo detectors are known with sufficient precision, but electronics may introduce different gains in processing physical data. For a correct interpretation of the information on I_0 we need to calculate a correction factor.

Using the Jacobi-Anger expansion from equation (5) it is possible to calculate analytically the amplitude of the second-harmonic, which is measured with a lock-in amplifier:

$$I_{2f}^{meas} = I_0\cos 2\varepsilon\cos 2\varphi_0 J_2(4\hat{\phi}_F) \qquad (8)$$

Combining (8) with (6a) it is also possible to deduce an expression where the second-harmonic is theoretically calculated from only measured quantities:

$$I_{2f}^{th} = \chi\frac{J_2(4\hat{\phi}_F)}{J_0(4\hat{\phi}_F)} \qquad (9)$$

Fitting by least squares the measured second-harmonic (8) with the theoretically calculated value (9) will give the correction factor for the intensity I_0.

VI. AC CURRENTS MEASUREMENT

The signal processing given by equation (1) is poorly efficient when far from the ideal setting. Even if a good approximation using a 3rd order polynomial is possible, it does not take into account any variation of the working point or the ellipticity (due for example to temperature changes).

A different way to approach the problem consists in inverting the equation (5) with respect to the electrical current, as follows:

$$I_{el}^{AC} = \frac{1}{4NV}\left[\arccos\left(\frac{2I_{out} - I_0}{X_\varepsilon I_0}\right) - \arccos X_\phi\right] \qquad (10)$$

where $I_{out} = I_{dc} - I_{ac}\sqrt{2}$ is the output intensity.

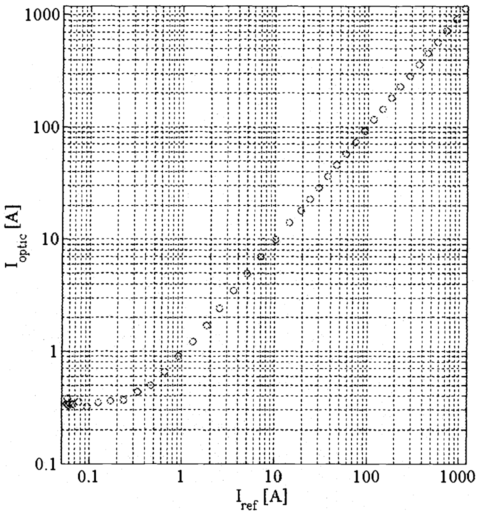

Fig. 5 Sensor optical-electrical AC transfer function obtained with $\phi_0 = 44.72°$ and $\varepsilon = 18.23°$

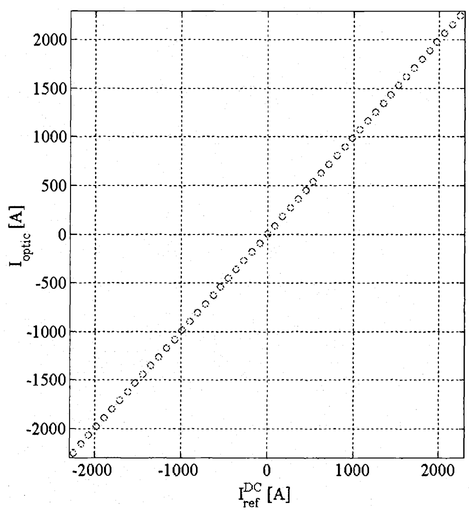

Fig. 6 Sensor optical-electrical DC transfer function obtained with $\phi_0 = 44.72°$ and $\varepsilon = 18.23°$. A factor scale correction of 0.92 has been operated

The working point X_ϕ and the ellipticity angle X_ε are previously calculated using the equations (7) by mean of an AC calibration, after having properly calculated the correction coefficient for I_0.

Figure 5 shows the optical-electrical transfer function of the sensor obtained with $\phi_0 = 44.72°$ and $\varepsilon = 18.23°$.

VII. EXTENSION TO DC CURRENTS

The approach described by the equation (10) offers the advantage of being easily applied to the measure of DC currents, with no significative modifications.

The AC components being absent of the output intensity signal, we have simply $I_{out} = I_{dc}$ and consequently:

$$I_{el}^{DC} = \frac{1}{4NV}\left[\arccos\left(\frac{2I_{DC} - I_0}{X_\varepsilon I_0}\right) - \arccos X_\phi\right] \tag{11}$$

where the operating point X_ϕ, the ellipticity angle X_ε and the correction coefficient for I_0 are the same as that used for the measure of AC currents.

The optical-electrical DC transfer function shown in Figure 6 is intrinsically linear: only a slight scale factor correction has been included.

For the moment, any variation of the operating point and of the ellipticity with temperature has been taken into account; some possibilities of improving the performances of the sensor are being investigated and an intelligent signal processing is being developed.

VIII. CONCLUSIONS

In this paper we present a polarimetric current sensor in a novel all-fiber configuration. It offers the key advantage to compensate any stray birefringence induced by additional elements like connecting fibers and connectors. This results in a very flexible configuration with a sensing fiber that may be wrapped around the conductor and then be connected to the instrument in the field. It makes this kind of sensor definitely portable that requires no interruption of the electrical conductor.

The configuration is easy to implement, at the expense of a more complex adjustment and signal processing. The all-fiber configuration makes the instrument very stable and immune to environmental issues and is therefore particularly well matched to the requirements of the end-user. Early results about stability and precision are promising and will certainly fulfill the performances expected for such an instrument.

REFERENCES

[1] F. Briffod, D. Alasia, L. Thévenaz, G. Cuénoud, and P.-A. Robert, "Extreme current measurements using a fibre optics current sensor" in Technical Digest of the 15th Optical Fiber Sensors Conference OFS'2002, Portland OR USA, IEEE Catalog number 02EX533, 2002, Postdeadline paper (PD3).

[2] A. H. Rose, M.N. Deeter, and G. W. Day, "Submicroampere-per-root-hertz current sensor based on the Faraday effect in Ga:YIG" Optics Letters, Vol. 18, pp. 1471-1473, September 1993.

[3] P.-A. Nicati and P.-A. Robert, "Stabilized current sensor using Sgnac interferometer" J. Phys. E: Sci. Instrum., Vol. 21, pp. 791-796, 1988.

[4] Patterson, A. H. Rose, D.Tang, and G. W. Day, "A fiber-optic current sensor for aerospace applications" presented at IEEE AES Systems Magazine, December 1990.

[5] P.-A. Nicati and P.-A. Robert, "Stabilized Sagnac optical fiber current sensor using one phase and two amplitude modulations" in Proc. 8th Optical Fibre Sensors Conference. Monterey, CA, January 1992, pp. 402-405.

[6] D. Tang, A. H. Rose, G. W. Day, and S. Etzel, "Annealing of linear birefringence in sinlge-mode fiber coils: Application to optical fiber current sensors" Journal of Lightwave Technology, Vol. 9, pp. 1031-1037, August 1991.

[7] R.Ulrich and A.Simon, "Polarization Optics of Twisted Single-mode Fibers" Applied Optics, Vol. 18, pp. 2241-2251, July 1979.

[8] F.Briffod, L.Thévenaz, P.-A. Nicati, A.Küng, and P.-A. Robert, "Polarimetric current sensor using an in-line Faraday rotator" IEICE Trans. Electron., Vol. E83-C, pp. 331-334, 2000.

[9] F. Briffod. *Structures innovantes pour capteurs optiques de courants électriques*. Ph.D. thesis, Swiss Federal Institut of Technology, Lausanne, 2003

[10] N. Pistoni and M. Martinelli, "Vibration-insensitive fiber-optic current sensor" Optics Letters, Vol. 18, pp. 314-316, 1993.