Fiber-Optic Current Sensor Tolerant to Imperfections of Polarization-Maintaining Fiber Connectors

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***Abstract*—We investigate the effect of polarization cross-coupling at polarization-maintaining (PM) fiber connectors on the accuracy of an interferometric fiber-optic current sensor. The sensor uses the Faraday effect in a fiber coil operated in reflection mode and an interrogator based on non-reciprocal phase modulation. PM connectors in the fiber link between the sensor's opto-electronic module and the fiber coil give rise to signal instability due to a limited and insufficiently stable polarization extinction ratio (typically <25-30 dB). As a result the accuracy of the sensor can be well outside the allowed tolerances of applications in the electric power industry which often demands accuracy to within ±0.2%. We demonstrate that by means of a modified optical circuit the disturbing effects of polarization-cross-coupling can be largely eliminated. The modified circuit introduces group delays for the cross-coupled light waves relative to the undisturbed waves much larger than the coherence length of the broadband light source. We theoretically and experimentally show that connector extinction ratios well below 20 dB are still uncritical. Furthermore, we verify the superiority of the modified circuit at changing connector temperature (and hence changing temperature-induced stress in the connector ferrules) and at repeated connector open-close operations.**

***Index Terms*—Current measurement, current transformer, Faraday effect, fiber-optic current sensor, interferometer, optical fiber sensor, polarization.**

I. Introduction

Fiber-optic current sensors (FOCS) employing the Faraday effect in optical fiber are being increasingly used for current measurement in high voltage (HV) substations for electric power transmission as alternatives to inductive instrument current transformers [1-5]. The optical sensors measure current, in particular transient fault currents, with higher fidelity due to the absence of magnetic saturation and large bandwidth. They provide high safety of operation, are environmentally friendly and ideally adapted to modern digital substation communication networks. The integration of the sensors into other HV devices, such as circuit breakers, can result in a substantial substation footprint reduction [5]. FOCS have also found significant interest in some industrial applications, in particular in the electro-winning of metals where they replace sophisticated Hall-effect-based current transducers [6].

Commonly the sensors employ a phase modulation technique derived from fiber-optic gyroscopes to measure the magneto-optic phase shift that the magnetic field of the current introduces between left and right circular light waves in a fiber coil around the current conductor [7-9]. A polarization-maintaining (PM) fiber connects the opto-electronic interrogation module with the fiber coil operated in reflection mode. The field installation of such sensors commonly involves PM fiber splicing, correspondingly trained personnel, and appropriate splice equipment. The alternative of polarization-maintaining fiber connectors would help to substantially simply and quicken the installation work. However, the polarization extinction ratio (PER) of commercially available PM connectors is far from being adequate for the needs of FOCS. Often the sensors must be accurate to within ±0.2% over wide temperature ranges (IEC metering class 0.2 [10]); high-end sensors in the electro-winning industry even must perform within ±0.1%. Adequate PM connectors would need to provide a PER of at least 32-34 dB. For comparison, the PER of commonly available commercial connectors often does not exceed 25 dB. The imperfections are due to tolerances in the relative angular alignment of the principal fiber axes of the two connected fiber sections and fiber stress in the connector ferrules. The first effect introduces random sensor scale factor variations at repeated connector open/close operations and the second effect extra temperature dependence of the scale factor, often with poor repeatability.

In the following, we investigate the influence of connector deficiencies on the sensor performance and demonstrate that with a modified optical circuit the sensor becomes largely immune to polarization cross-coupling at connectors [11]. The modified circuit introduces group delays for the cross-coupled light waves with respect to the uncoupled waves in excess of the coherence length of the broad band light source. As a result connector extinction ratios well below 20 dB are still uncritical.

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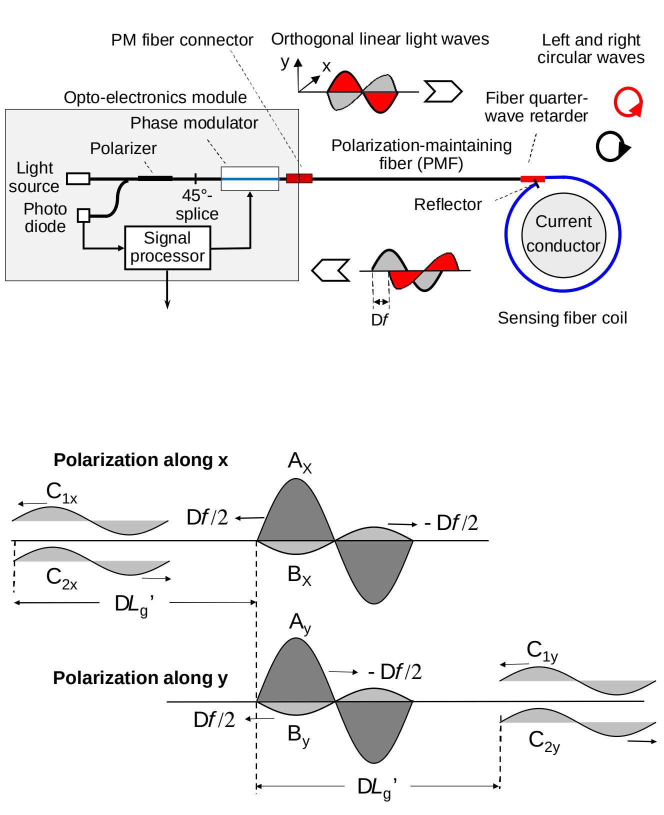

Fig. 1. Fiber-optic current sensor with type 1 optical circuit (top); interfering light waves in case of polarization cross-talk at PM fiber connector (bottom). The arrows indicate the direction of the magneto-optic phase shift $\Delta\varphi/2$ of the individual waves.

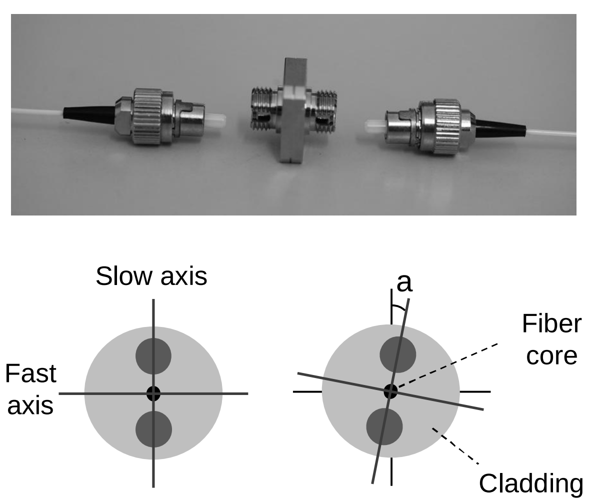

Fig. 2. FC/PC PM connectors with mating adapter (top); misalignment angle α between PM fiber principal axes of the two connector sides.

II. FOCS Optical Circuits With Imperfect PM Fiber Connectors

In the well-known FOCS circuit (type 1 circuit, Fig. 1, top) the opto-electronics module sends a pair of orthogonal linear polarization states (here at 1305 nm) via a polarization-

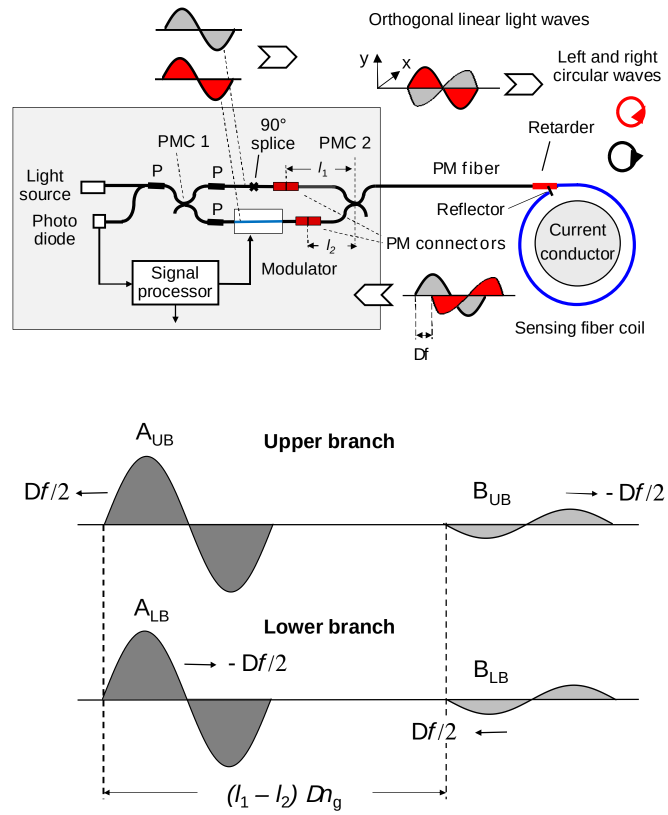

Fig. 3. Fiber-optic current sensor with type 2 optical circuit (top), P = polarizer, PMC = polarization-maintaining fiber coupler; interfering light waves in case of polarization cross-talk at PM fiber connectors (bottom), UB = upper branch, LB = lower branch.

maintaining fiber link to the fiber coil around the current conductor [7-9]. A fiber quarter-wave retarder, typically from elliptical-core fiber for low temperature dependence, converts the linearly polarized waves into left and right circular waves that are coupled into the sensing fiber [12]. The two light waves are reflected at the far end of the fiber coil and return with swapped polarization states to the opto-electronics module where they interfere at the polarizer. Due to the Faraday effect the two circular light waves accumulate in the coil a differential magneto-optic phase shift given by $\Delta\varphi = 4VNI$, where V is the Verdet constant (~1.0 μrad/A at 1305 nm), N is the number of fiber loops, and I is the current. A closed-loop detection circuit [13] with an integrated-optic lithium niobate birefringence modulator recovers the magneto-optic phase shift. Note that due to the swapping of the circular polarization states at the reflector the birefringent group delays in the PM fiber and the modulator cancel each other over a full roundtrip.

Polarization cross-coupling at the indicated PM fiber connector during the forward and return travel of the light gives rise to three additional pairs of orthogonal light waves which affect the recovered magneto-optic phase shift. Fig. 1 (bottom) illustrates the four returning wave pairs that finally interfere at the polarizer. The A-waves (A_x, A_y) are the fractions which did not experience any cross-coupling and have (relative) amplitudes of $\cos^2\alpha$. Here, α is the misalignment angle between the principal axes of the two connected fibers (Fig. 2). (We assume that the original pair of orthogonal waves are generated with equal amplitudes and attribute at this point all cross-coupling to connector misalignment but do not consider stress in the connector ferrules as another potential cause). The B-waves (B_x, B_y) result from cross-coupling both on the forward and return paths and hence have amplitudes of $\sin^2\alpha$. Like the A-waves the B-waves return with zero differential group delay but have, without applied current, a phase shift of 180° with respect to the A-waves, a consequence of the polarization swapping by the fiber retarder and mirror combination. Finally, the two pairs of C-waves ($C_{1,x}$, $C_{1,y}$ and $C_{2,x}$, $C_{2,y}$) are the result of single cross-coupling, on the forward or return path, respectively, and have amplitudes of $\cos\alpha\ \sin\alpha$. They accumulate birefringent group delays $\pm\Delta L_g'$ with respect to the A and B waves, where $\Delta L_g'$ is the delay between the 45°-fiber-splice behind the polarizer and the connector (with contributions from the modulator and the PM-fiber sections before and after the modulator). Since $\Delta L_g'$ is typically much larger than the coherence l_c of the broadband superluminescent diode light source the C-waves have only very minor influence on the recovered signal. The 180°-phase-difference of the A and B waves and the fact that the A and B waves of a given polarization experience magneto-optic phase shifts, $\Delta\phi/2$, in opposite directions (arrows in Fig. 1, bottom) result in an apparent magneto-optic phase shift between x and y polarized light that is enhanced and given by

$$\Delta\phi(\alpha) = \Delta\phi_0 / \cos(2\alpha) \tag{1}$$

with $\Delta\phi_0$ being the phase shift at $\alpha = 0$. Equation (1) follows from a description of the optical circuit by Jones matrices. The additional light waves (B and C waves) and corresponding scale factor change are the same as in case of a fiber quarter-wave retarder at the coil entrance that deviates by 2α from perfect 90°-retardation [6, 7, 9, 14]. (Note that the increase in apparent phase shift and hence signal amplitude is accompanied by a decrease in the signal-to-noise ratio due to reduced fringe visibility). Hence, an angular tolerance of, e.g., ±3°, which corresponds to a PER of 25.6 dB and is not untypical for PM connectors, translates into a signal uncertainty within 0.56%, which is unacceptable in many sensor applications. In the case of FC/PC connectors as illustrated in Fig. 2 the misalignment α is composed of contributions from the orientation of the fiber in the connector ferrule, the ferrule holder inside the connector body (the latter is commonly the dominating contribution), and the relative orientation of two the connector bodies in the mating adapter.

The optical circuit (type 2 circuit) shown in Fig. 3 (top) introduces a group delay between the A and B waves significantly larger than the coherence length (Fig. 3, bottom) and thereby drastically reduces the influence of the cross-coupled light on the sensor signal. We have introduced this circuit type in [6] in order to be able to interrogate the in-line fiber coil by means of a lithium niobate phase modulator with a Y-type waveguide layout as used in fiber gyroscopes. In the present case, a first PM fiber coupler (PMC1) splits the light into two waves that initially propagate with parallel polarization states in an upper and lower fiber branch. As a result of a 90°-splice in the upper branch the two waves combine in a second PM fiber coupler (PMC 2) to two orthogonal waves which then again proceed towards the fiber coil. The orthogonal light waves returning from the coil again divide themselves at PMC2 into the two branches. Note that only those waves are allowed to interfere with each other which have travelled along mutually equal paths, that is in the upper branch on the way forward and the lower branch upon return and vice versa and also have travelled with mutually equal polarization states; see [6, 15] for more details. The two branches now include two PM connectors at distances l_1, l_2, respectively, from coupler 2. The asymmetric connector positions introduce a group delay between the A and B waves given by $(l_1 - l_2)\,\Delta n_g$ with Δn_g being the group birefringence of the PM fiber. This delay can easily be made much larger than the coherence length so that the B waves only interfere among themselves but no longer with the A waves. Hence, the influence of the B waves on the apparent magneto-optic phase shift and sensor scale factor is drastically reduced. (The C waves become fully irrelevant as they are blocked by the polarizers or incoherent). The A and B waves give rise to two essentially independent interference signals in proportion to $\cos^4\alpha$ and $\sin^4\alpha$, respectively, the intensities of which add up at the photodetector. The recovered magneto-optic phase shift as a function of the misalignment angle α can then be written as

$$\Delta\phi(\alpha) = \Delta\phi_0\ (\cos^4\alpha - \sin^4\alpha) / (\cos^4\alpha + \sin^4\alpha) \tag{2}$$

Here, we assume identical misalignment angles α at the two connectors. The minus sign of the ($\sin^4\alpha$)-term in the nominator of (2) reflects the opposite magneto-optic phase shifts of the A and B waves. It should be noted that there is no scale factor change if cross-coupling occurs only at one of the two connectors. In that case the cross-coupled light will be blocked on the return path at the polarizers. Note also that the apparent magneto-optic phase shift disappears at $\alpha = 45°$. Again assuming a misalignment of 3°, the relative scale factor change is now reduced from $5.6\text{x}10^{-3}$ (type 1 circuit) to only $1.5\text{x}10^{-5}$ (type 2 circuit). In fact, according to (2), α can be increased (for both connectors) to 17.5°, corresponding to a PER of 10 dB, until the error exceeds 0.2%.

III. Experimental Verification and Discussion

Fig. 4 compares theoretical and experimental results for the normalized sensor scale factor (corresponding to the term $\Delta\phi(\alpha)/\Delta\phi_0$) as function of the misalignment angle α for the two circuits [11]. The experimental data were obtained by representing the connectors in Fig. 1 and Fig. 3 by PM fiber splices (Panda fiber) with various offset angles α between the principal fiber axes ranging from zero to about 16 degrees (Fujikura PM fiber splicer FSM-100P). In order to largely eliminate uncertainty in α, for each α two or more pairs of fiber sections were spliced together. The actual value of α was then determined by launching polarized light through the

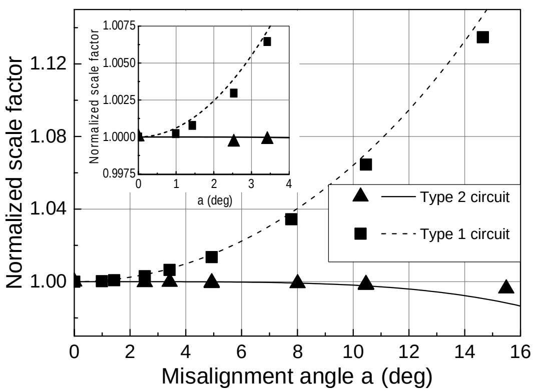

Fig. 4. Normalized scale factor vs connector misalignment angle α for type 1 and type 2 optical circuits (experiment and theoretical models). The inset shows the data on an expanded scale.

spliced fiber pairs and measuring the extinction ratio. Subsequently the fiber pairs with the appropriate offset angles were spliced into the circuits with zero-degree splices at both ends, i.e., the splice with the offset angle was between the two zero-degree splices. The estimated error in the splice angles is about ±1°. The fiber coil consisted of four windings of low birefringent sensing fiber (fiber diameter of 80 μm) packaged in a thin capillary of fused silica [6, 16]. The coil diameter was 170 mm, i.e., the fiber length was 2.14 m. The residual intrinsic birefringence of the sensing fiber corresponded to a retardation of 2-4 degrees, whereas the retardation due to bend-induced birefringence was about 16 degrees. The data were taken at a constant applied DC current of about 2 kA (resulting in a magneto-optic phase shift of about 32 mrad). The signal at each angle was averaged over a few minutes which resulted in a signal uncertainty of <0.02%. It is obvious that the experimental data for the two circuits (squares and triangles) agree well the theoretical models and confirm the high tolerance of the type 2 circuit against connector-related polarization cross-coupling.

Further experiments were done with actual connectors instead of offset splices. The connectors were FC/PC PM connectors that were custom-made for reduced angular tolerances. The misalignment between the principal axes of the joint fibers was within about ±1.8° corresponding to a PER of 30 dB or better. For comparison, the alignment tolerances of more standard FC/PM PM connectors are seldom better than ±3° (the corresponding extinction ratio is about 25 dB as already mentioned further above). However, even with reduced angular tolerance fiber stress in the connector ferrules can suppress the PER to values well below 30 dB in a temperature-dependent manner. Fig. 5a shows the measured PER of such a connector over multiple temperature cycles between -40 and 65°C. The extinction ratio varies between about 27.3 dB and 30.8 dB. Subsequently, the connector was spliced into a sensor with a type 1 circuit. Fig. 5b depicts the sensor signal as a function of the connector temperature (all other sensor components remained at room temperature). The signal varies within about 0.1% and reflects well the variation

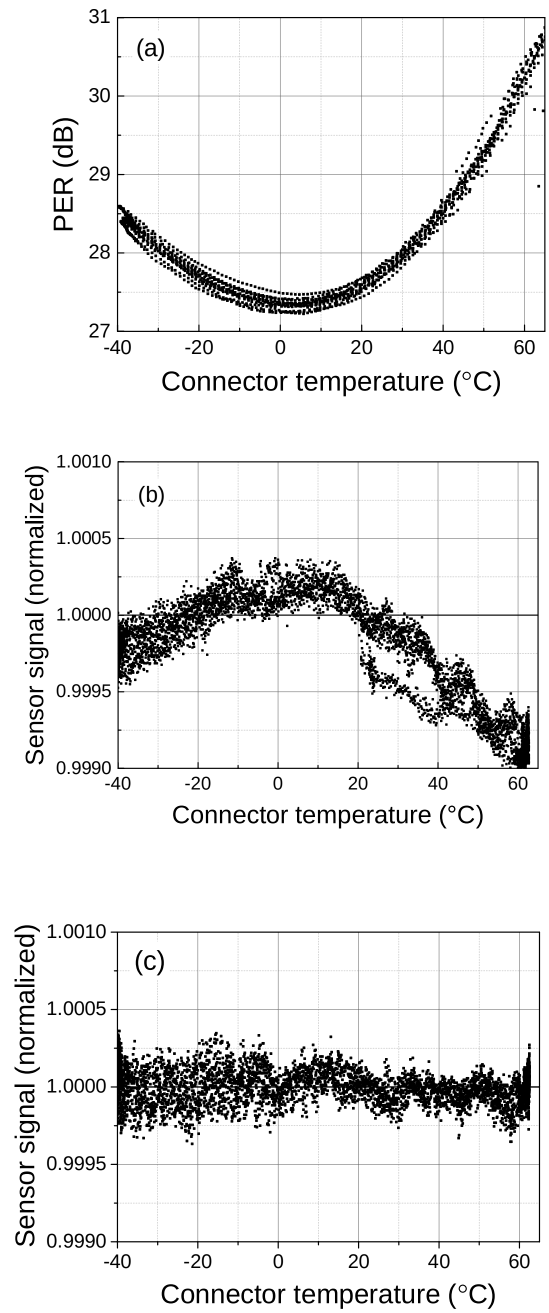

Fig. 5. (a) Connector polarization extinction ratio (PER) vs. connector temperature, (b) sensor signal with type 1 optical circuit vs. connector temperature, (c) sensor signal with type 2 optical circuit vs. connector temperature.

of the connector PER with temperature, even though the peak-to-peak variation in the signal is somewhat less than expected from the PER. (As noted in context of (1), a decreasing PER enhances the apparent magneto-optic phase shift and hence the sensor signal). For comparison this connector and a second connector of similar performance were spliced into the type 2 circuit at the indicated connector locations (Fig. 3). The length difference l_1 - l_2 of two fiber sections between the connectors and the coupler PMC2 was about 1.5 m. The corresponding difference in group delays $(l_1 - l_2)\,\Delta n_g$ was 570 μm and hence

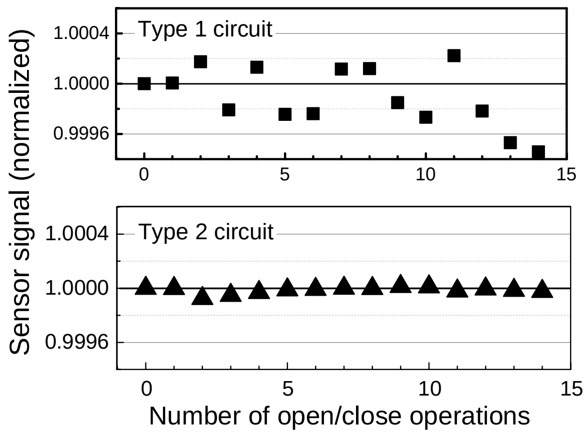

Fig. 6. Sensor signal repeatability at connector open/close operations for type 1 and type 2 circuits.

much larger than the coherence length of the light source (about 30 μm). Fig. 5c again shows the sensor signal as a function of the common temperature of the two connectors. The signal remains stable well within ±0.05% and does not exhibit any noticeable influence of the temperature dependent connector PER.

In a further test, we compared the signal stability of the two circuits at repeated connector open-close operations (Fig. 6) [11]. Open-close operations can change the angle α within the angular tolerances of the connector and may also result in modified fiber stress fields in the connector ferrules. Whereas with the type 1 circuit we observed signal variations within ±0.05%, the variations were reduced to less than ±0.01% with the type 2 circuit. Again, it should be pointed out that the used connectors were custom-made for reduced angular tolerances. This results in a relative good signal repeatability even with the type 1 circuit. Nevertheless, a ±0.05%-uncertainty already consumes a quarter of the overall error budget (±0.2%) of a sensor according to IEC class 0.2 requirements. Significantly larger signal variations can be observed with the type 1 circuit if standard PM connectors are employed.

The immunity of the type 2 circuit to poor connectors can be further improved if PM coupler 2 is replaced by a polarizing beam splitter (PBS). The PBS in combination with polarizers blocks the B-waves so that only the A-waves contribute to the signal. In corresponding experiments the observed scale factor changes remained within 0.025% (that is essentially the measurement uncertainty) for misalignment angles up to 20 degrees.

It should be noted that imperfections of the PM coupler 2 or the PBS may result in a minor dependence of the scale factor on the coupler or PBS temperature. Scale factor changes between -40 and 60°C of about 0.1% and 0.05% (peak-to-peak) were observed for the coupler and PBS, respectively and correlated with the variation of the PER between the coupler or PBS ports (all other components including the connectors remained at room temperature). As the changes are well repeatable they can be easily compensated, so that they do not significantly stress the error budget (±0.2%) of a class 0.2 sensor. By contrast, it is commonly not possible to compensate connector-related errors of the type 1 circuit in this way. Even though the signal as a function of the connector temperature may be well repeatable as shown in Fig. 5b, opening and closing the connector can randomly change both, the scale factor at a given temperature and, to some extent, how the scale factor varies with the connector temperature. The first effect is mainly related to a change in α, whereas the second effect is attributed to modified stress fields in the short fiber sections within the connector ferrules.

Furthermore, we would like to note that the type 2 circuit also puts less demands on the PER of the modulator. In the type 1 circuit polarization-cross-coupling, in particular at the coil-side fiber pigtail of the modulator, will affect the signal [17], whereas we find that the effect is very much suppressed with the type 2 circuit. However, some care should be taken to geometrically arrange the two fiber branches of the type 2 circuit such that the enclosed area is minimized in order to suppress rotation-induced phase shifts of the interfering waves due to the Sagnac effect [13]. One should also mention that, as a matter of principle, the type 2 circuit is somewhat more sensitive to mechanical disturbances such as vibrations than the type 1 circuit analogue to the difference between a Sagnac-type current sensor and an in-line current sensor [8, 9]. Since the two separate fiber branches are relatively short, the differences are of little relevance in practice, though.

Finally, we would like to point out that one can take advantage of intentional polarization cross-coupling at appropriately configured fiber retarders in both optical circuits for certain compensation purposes, e.g., for the compensation of the temperature dependence of the Faraday effect or source wavelength changes [6, 9, 18].

IV. Conclusion

We have demonstrated an optical circuit (type 2 circuit) for fiber-optic current sensors that reliably eliminates disturbance of the sensor signal as a result of cross-coupling between the two orthogonal polarization modes of the sensor at imperfect polarization-maintaining fiber connectors. The circuit is somewhat more complex than the more conventional type 1 circuit but has the advantage that splicing of polarization-maintaining fiber during field installation of the sensor can be avoided. The two PM connectors are preferably located at the opto-electronics module of the sensor. PM coupler 2 (or alternatively a polarization-maintaining beam splitter) of the circuit are then part of the termination of the PM fiber cable between the sensor's opto-electronics module and the fiber coil.

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