Electrical Current Metering With a Dual Interferometric Configuration and Serrodyne Signal Processing

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Introduction

Optical technology for the measurement of electrical current in high voltage environments has experienced a considerable development in the last decade[1, 2]. Due to the intrinsic dielectric characteristics of optical sensors the need for insulation is greatly reduced. Most configurations are based on the Faraday effect, which has a constant linear response over a wide range of frequencies and, unlike conventional sensors, presents no hysteresis or saturation effects for realizable fields. Bulk closed loop configurations are especially attractive because their closed optical path ensures immunity to external magnetic fields, allowing therefore univocal current measurement. Also, bulk materials with high Verdet constant and small stress-optical coefficient can be chosen that minimize the linear birefringence problems common to all-fiber configurations[3]. Following these ideas, some closed bulk optical circuit solutions have been presented, such as a triangular critical angle reflection sensing head[4] or a square shaped sensing head with double complementary reflections in the corners[5].

The Faraday effect consists in a circular birefringence induced in the medium by the presence of a magnetic field. This causes a linear polarized state to rotate its plane of vibration by an angle θ_F given by:

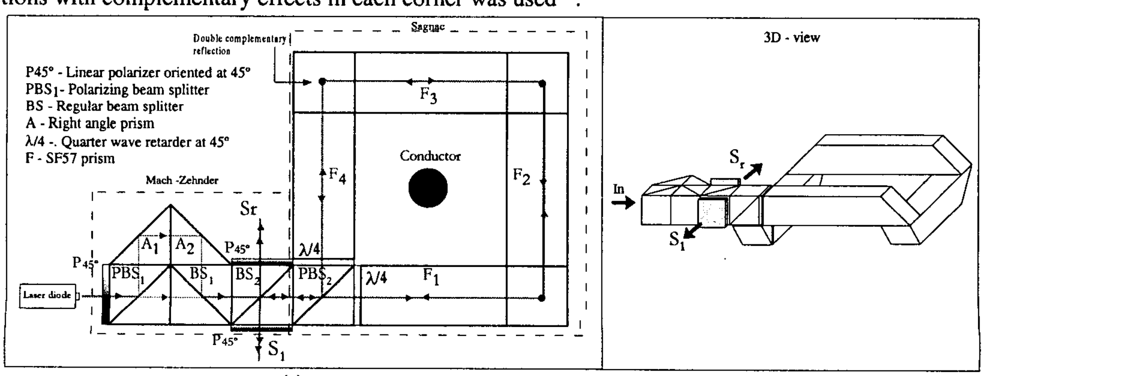
$$\theta_F = \int_L V\,\vec{\mathbf{H}}\cdot\vec{\mathbf{dl}} \qquad (1)$$

where V is the material-dependent Verdet constant, $\vec{\mathbf{H}}$ is the magnetic field and L is the interaction length. In most bulk configurations the polarization azimuth current dependence is converted into an optical power modulation with a polarimetric scheme. Typically the detected irradiance exhibits a sinusoidal dependence with the azimuth angle. This means that the working range must be restricted to the linear part of the transfer function, or some kind of feedback must be used in order to linearize the output. Also, the optical power fluctuations due to vibrations or optical source instability must be compensated by some reference scheme in order to recover the measurement information without ambiguity.

The scheme introduced here is a bulk interferometric configuration where the measurement information appears as a phase modulation of a high frequency carrier. In this way the sensor transfer function is independent of optical power fluctuations and has truly linear dependence with the current.

Principle of Operation

The proposed sensing head, represented schematically in figure 1, is a Mach-Zehnder processing interferometer with an additional reciprocal loop. The square shaped loop, consisting of a Sagnac interferometer, is built with low linear birefringence *SF57* glass prisms. In order for the beam to remain confined within this loop, internal reflections are needed at the corners. To avoid unwanted phase terms the technique of double reflections with complementary effects in each corner was used[5].



(a) (b)

Figure 1 – Schematic representation of the proposed configuration (a); 3D view (b).

Linear polarized light entering the first interferometer is split by PBS_1 in two orthogonal linear modes that follow different paths. These modes are recombined in the Mach-Zehnder outputs. When viewed through a linear polarizer oriented at 45°, an interferometric reference signal is obtained in one of BS_2 outputs (S_r). The optical path imbalance between the two beams allows a high frequency carrier to be generated by ramping the laser diode injection current. The optical radiation that is not reflected towards the polarizer at the third beam splitter (BS_2) illuminates the square loop. At this point the orthogonal linear modes are converted, by the $\lambda/4$ retardation plates oriented at *45°*, in two counter-propagating orthogonal circular modes. After encircling the loop the two circular modes, passing once again through the retardation plates, are converted back into linear orthogonal modes. This radiation is reflected in BS_2 and after passing through a linear polarizer at *45°* originates an interferometric output signal (S_l). Due to the circular birefringence induced in the square loop by the magnetic field, a phase difference is introduced between the two orthogonal circular modes that is proportional to the current under measurement. This way the pseudo-heterodyne carrier generated in the interferometer is phase modulated by the measuring current.

This configuration has several advantages for use in current measurements. The measurement information, which is contained in the carrier's phase, is not corrupted by optical power fluctuations. Furthermore, the Sagnac topology is intrinsically insensitive to reciprocal effects like those induced by vibrations or temperature fluctuations and depends only on non-reciprocal effects like the Faraday effect. Also, the use of serrodyne demodulation avoids low frequency electronic noise. The phase information in output S_l is extracted with a lock-in amplifier using output S_r as a reference signal. This provides some degree of immunity to the optical source spectral instability and the corresponding phase noise.

The proposed system can easily be analyzed using Jones calculus matrix notation[6] under ideal conditions. When the injection current of the laser diode is modulated with a signal of frequency ω and amplitude required to sweep the interferometer over 2π phase, outputs S_l and S_r would be function of time as;

$$S_r = \frac{E_0^2}{8}(1 + cos[\omega t + \phi_0]) \tag{2}$$

$$S_1 = \frac{E_0^2}{16}(1 + cos[\omega t + 2\theta L + \phi_0]) \tag{3}$$

Equations (2) and (3) are derived by ignoring the effect of fly-back distortion on the signals since this could be easily achieved via band-pass filtering. In these equations the term ωt results from the time variation imposed to the phase by the laser wavelength modulation and ϕ_0 is the quasi-static phase of the Mach-Zehnder interferometer that also includes the effect of environmental perturbations and the impact of instability of laser's wavelength. Thus two carrier signals are obtained: a reference signal with a quasi-static phase and an output signal with its phase modulated by the current to be measured. Using these two signals in a lock-in amplifier their relative phase can be obtained:

$$\phi_r = 2\theta L + \phi_0 - \phi_0 = 2\theta L \tag{4}$$

This phase information can be related to the current passing trough the conductor using equation (1) to calculate θ:

$$\theta = 2\frac{V}{L}\frac{\mu_0 I}{2\pi}arctan\left[\frac{L}{2r}\right] \tag{5}$$

where I is the electrical current, r is the distance between each prism and the conductor and μ_0 is the magnetic permeability of the medium (assumed non-magnetic).

With these expressions it becomes possible to predict the behavior of the sensor transfer function. The parameters of our system are: λ*=850 nm*; $V_{(SF57\ Glass)}$ *≈11.7 rad/(m.T)*; *r≈5 cm*; *L≈38 cm* (each side of the square loop is *9 cm*). With these parameters it can be theoretically predicted that phase ϕ_r will experience an excursion of approximately *360°* when a current of *217 kA* is flowing through the conductor. This results in a sensitivity of *1.7°/kA*. Although this is a small value, this type of sensors is typically used to measure large electrical currents. The specific performance in terms of current resolution will, as always, be dependent on the minimization of the several noise sources present in the measurement system.

Experimental Results

The experimental setup used to demonstrate the feasibility of the proposed current sensor design is shown in figure 2. A single mode laser diode (Hitachi – HL8311E) operating at *830 nm* with a *7 mW* output power was used. To avoid back reflections into the laser cavity the input optical fiber end was cut in angle and an optical isolator was placed between the collimating and injection lenses. The sensing head was connected to the optical source and the detection and processing electronics through a *50 m* optical fiber cable. A single mode optical fiber carries optical power to the sensing head and two multimode fibers carry the output signals to detection. A low voltage current source providing outputs from zero to *2000* A_{rms} and operating at *50 Hz* was used to generate current to be measured. The laser injection current was modulated at *2 kHz* with a saw-tooth waveform and the amplitude of the signal was adjusted to $\approx 1.6\ mA$ in order to obtain a 2π phase modulation in the Mach-Zehnder interferometer (which had an optical path imbalance of $\approx 6\ cm$). The phase of carrier S_1 was measured relative to the reference signal S_r using a lock-in amplifier. The lock-in output was fed into an electrical spectrum analyzer where an electrical signal proportional to the phase at *50 Hz* ($V_{\phi 50Hz}$) was monitored.

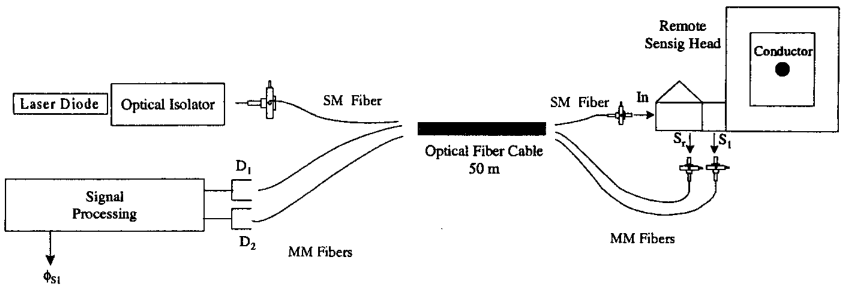


Figure 2 – Experimental set-up implemented to test the proposed configuration.

Linearity test results (phase amplitude at *50 Hz* vs. applied current) are presented in figure 3. A good correlation between experimental data and linear fit can be observed. The system sensitivity can also be estimated as *1 °/kA*. This result is in fair agreement with the theoretical predictions of *1.7 °/kA* considering various assumptions were made to create a simple theoretical model.

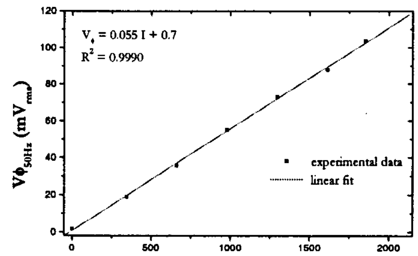
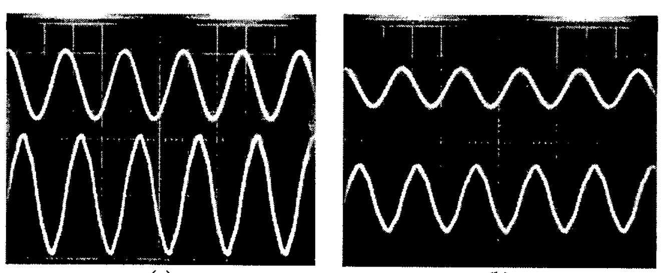


Figure 3 – Experimental data showing phase behavior with the applied current.

The system functionality was tested by comparing the measured signal with the original current waveform that goes through the conductor. In figure 4, upper traces are the measured signals and lower traces are the current waveform with values of *1613* A_{rms} and *819* A_{rms}. In order to obtain the current waveform, a coil was incorporated in the vicinity of the conductor that introduces a $\pi/2$ phase shift in the induced signal. We also observed that the measured waveforms (upper traces) have been filtered as the lock-in bandwidth was set to a value slightly higher than *50 Hz*. The important point to note is that the behavior of the sensor is identical for two different *rms* values of current.

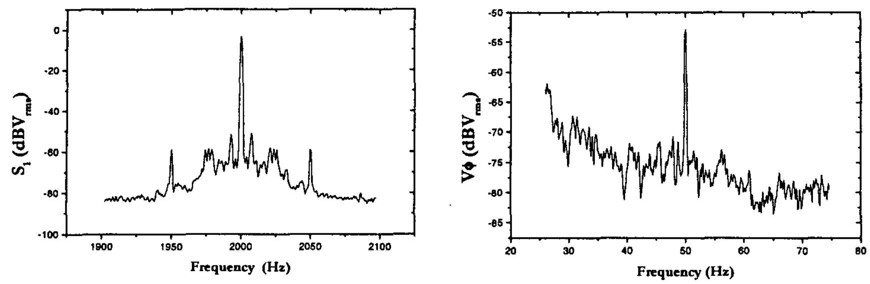


(a) (b)

Figure 4 – Evaluation of waveform reproduction. Signal proportional to the applied current phase shifted by $\pi/2$ (lower trace) and measured waveform (upper trace), for a current passing trough the conductor with amplitudes of (a) *1613* A_{rms}; (b) *819* A_{rms}.

System resolution can be calculated by measuring the signal to noise ratio directly from the electrical spectrum. Figures 5a and 5b show the spectra of the electrical carrier and the recovered phase waveform respectively when a current of *100* A_{rms} was passing through the conductor. A signal to noise ratio of *24.4 dB* can be measured in the phase spectrum, which corresponds to a resolution of $17\ A_{rms}Hz^{-1/2}$. Another way to determine the resolution is by real time monitoring of the *rms* amplitude of the output phase waveform when the *rms* amplitude of the current waveform in the conductor is stepped by a certain value. This procedure is illustrated in figure 6 for a *rms* current step of *108* A_{rms}.

The analysis of the data in figure 6, when considering the detection bandwidth (*122 mHz*), indicates a resolution of $\approx 22.4\ A_{rms}Hz^{-1/2}$, a value close to the one obtained with the alternative spectral approach. This not so good resolution was attributed to the high level of phase noise present in the system. In fact, it was found that for the particular laser diode utilized in the experiment the modulation of its injection current induced significant spectral instability. This instability was then translated to the intensity noise via the optical path imbalance ($\approx 6cm$) of the Mach-Zehnder interferometer. It is believed that a significant improvement in the system resolution would be achieved if the wavelength of the laser was stabilized.



(a) (b)

Figure 5 – Spectra obtained when a current of *100 A_{rms}* was passing trough the conductor: (a) carrier S_1; (b) phase ϕ_{S1}.

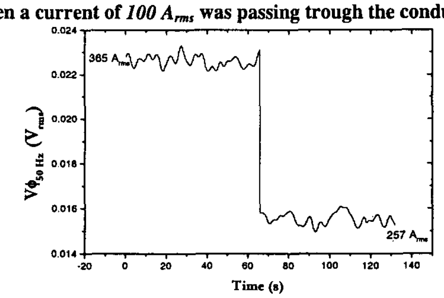


Figure 6 – Amplitude (*rms*) of the output phase signal at *50 Hz* when a current step of *108 A_{rms}* is applied.

The consideration of serrodyne processing limits measurement bandwidth to a value that should not exceed one tenth of the carrier frequency. This feature of the proposed system is sufficient for electric current metering applications but is not suitable in relaying applications, i.e., on the monitoring of current line transients. However, this is not an intrinsic limitation of the sensor design shown in figure 1. Indeed, active homodyne processing could be implemented by using S_1 to feed a feedback loop that would act on the laser diode injection current in order to keep the interferometer system in a fixed point of its transfer function (typically in quadrature). With such processing the information about the electrical current flowing along the conductor would be obtained from the value of the laser diode injection current. The measurement range and bandwidth depend only on the wavelength tunability of the laser diode radiation and on the bandwidth of the feedback loop, respectively.

Conclusion

Theoretical and experimental results were presented which validated a new dual interferometric configuration with serrodyne processing for the remote sensing of electrical current. Linearity and waveform reproduction at *50 Hz* were observed and a current resolution ($\approx 22.4\ A_{rms}Hz^{-1/2}$) was obtained. The utilization of the proposed interferometric concept to simultaneously perform metering and relaying current measurements was also addressed.

References

1. Y.N. Ning, Z.P. Wang, A.W. Palmer, K.T.V. Gratan, *"Recent progress in optical current sensing techniques"*, *Review of Scientific Instruments*, vol.5, 66, p. 3097-3111, (1995).
2. B.T. Meggit and K.T.V. Grattan, *Optical Fiber Sensor Technology: Applications and Systems,* Kluwer Academic Publishers, 1999.
3. Peter R. Forman and F.C. Jahoda, *"Linear birefringence effects on fiber-optic current sensors"*, *Applied Optics*, vol.27, 15, p. 3088-3096, (1988).
4. B.C.B. Chu, Y.N. Ning, and D.A. Jackson, *"Faraday current sensor that uses a triangular-shaped bulk-optic sensing element"*, *Optics Letters*, vol.17, 16, p. 1167-1169, (1992).
5. Tadashi Sato, Genji Takahashi, and Y. Inui, *Method and apparatus for optically measuring a current*, US Patent n° 4564754, Hitachi, 1986.
6. N.C. Pistoni, *"Simplified approach to the Jones Calculus in retracing optical circuits"*, *Applied Optics*, vol.34, 34, (1995).