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Optimal design of optical fibers for electric current measurement

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The current sensitivity and bandwidth of the optical fiber current monitor are analyzed. The optimal sensitivity is proportional to the ratio of fiber attenuation to the Verdet constant at a specific fiber length. A selection of compound glasses has been investigated with a view to improving bandwidth and sensitivity over standard silica–fiber systems. A trial fiber of the most promising glass (Schott F7) has been fabricated and characterized.

Owing to their high electrical isolation and large bandwidth, there is at present much interest in the use of optical fibers to measure electrical current.[1,2] The sensor consists of a number of fiber coils wound around a current carrying conductor. By virtue of the Faraday effect, the current flow induces a rotation of the plane of polarization of the light traversing the fiber. The rotation is measured by an analyzer and depends on the magnitude of the current, the number of fiber turns, and the Verdet constant of the material. The bandwidth of the device is determined by the transit time of the light through the fiber coil.

To date, fiber current sensors have used silica telecommunications fiber[1] because of its low loss. However, the Faraday effect in silica is comparatively weak, and this limits the current sensitivity, particularly when using a short length of fiber so as to reduce the optical transit time and thus obtain a high bandwidth. Compound glasses can have considerably higher Faraday rotation (up to 10 times higher than silica) but have an optical loss which restricts their use to lengths between 1 m and a few tens of meters, depending on the glass.

As a result of the interplay between optical loss and the Verdet constant, the sensitivity of the fiber current sensor depends critically on the length of the fiber and an associated choice of optical glass. Using data for a number of Schott[3] glasses, we examined the options available and determined that for coil lengths between 15 and 50 m (corresponding to bandwidths of 5.5 and 1.6 MHz) F7 glass is the best choice, after which silica-based fibers are preferred. A fiber-based on F7 glass has been fabricated and measured to confirm the predictions. The fiber provides a 2.5-fold increase in the Verdet constant over silica with a loss potentially as low as 0.2 dB/m.

The optical configuration and signal processing used by Smith[1] is taken as the basis for an analysis of the current sensitivity. For small Faraday rotations the response of an N-turn fiber coil of diameter d to a current I is

$$R(I) = \sin(2VNI) \approx 2VNI = \frac{2VLI}{\pi d}, \tag{1}$$

where V is the Verdet constant (rad/A) and L is the length of fiber comprising the coil. The minimum current that can be resolved is limited by the receiver noise. For strong received optical signals (>0.5 mW) the photocurrent shot noise will dominate the noise characteristics of the PIN photodiode/silicon FET transimpedance[4] preamplifier employed. Thus the detection noise $R(n)$ is given by

$$R(n) = \left(\frac{2|e|B}{R_e P_r}\right)^{1/2} \tag{2}$$

Here $P_r = P_1 10^{-\alpha L 10^{-4}}$ is the received optical power, P_1 the launched power, e the electronic charge, B the measurement bandwidth, R_e the responsivity of the photodiodes (A/W), and α the fiber attenuation (dB/km). From the above we obtain an expression for the noise equivalent current I_e normalized to the coil diameter d:

$$\frac{I_e}{d} = \frac{\pi}{2VL}\left(\frac{2|e|B}{R_e P_1 10^{-\alpha L 10^{-4}}}\right)^{1/2}. \tag{3}$$

The length of fiber L_{max} at which Eq. (3) exhibits a minimum can be calculated:

$$L_{max} = \frac{2 \times 10^4}{\alpha \log_e 10}. \tag{4}$$

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At this optimal length the normalized noise equivalent current is

$$\frac{I_e}{d}\bigg|_{L_{max}} = \left(\frac{\alpha}{V}\right)\frac{\pi \log_e 10}{4\times 10^4}\left(\frac{2|e|B}{R_e P_1 10^{-2/\log_e e^{10}}}\right)^{1/2}. \quad (5)$$

The Verdet constant and optical loss values for a range of glasses are given in Table I from data supplied by Schott.[3] The loss values were calculated from the internal transmittance of 25-mm samples; consequently, the accuracy of these values is poor for the low loss glasses.

Curves of current sensitivity normalized to coil diameter (I_e/d) against fiber length are given for a selection of the most useful glasses in Fig. 1. The curve for silica-based fibers is also given in the figure for comparison. Typical values for a current monitor have been assumed, namely, an operating wavelength of 633 nm with 1 mW of launched power, a bandwidth of 1 Hz, and a photodiode responsivity of 0.4 A/W. With reference to Fig. 1, it can be seen that the choice of glass for the highest sensitivity depends on the length of fiber employed. Of the glasses examined, the greatest sensitivity is obtained using SF57 up to a length of ~15 m, then with F7 up to a length of 50 m. As a consequence of its low loss, silica is the clear choice for all longer lengths.

The greatest current sensitivity for a particular glass can be calculated from Eq. (5). This value is dependent on the ratio of optical loss to Verdet constant for a given set of operating conditions. In previous work[5] this parameter has been suggested as a figure of merit for the Faraday rotator. It is interesting to note that the performance of a fiber with regard to current sensitivity is also characterized by this ratio. The loss to Verdet constant (α/V) ratios for the glasses investigated are given in Table I. Evidently, silica is at least 1 order of magnitude superior to the compound glasses in this respect, although it must be remembered that the loss figures used here for the compound glasses are almost certainly dominated by the impurity content. For example, a fiber of similar composition to F7 has been fabricated with a minimum loss of 60 dB/km.[6]

Despite the superior performance of silica at the optimum length, in cases where the system bandwidth is an important criterion, the length of the fiber will be necessarily restricted to lengths shorter than the optimum. In this situation, compound glasses with short optimal lengths offer better current sensitivity than silica.

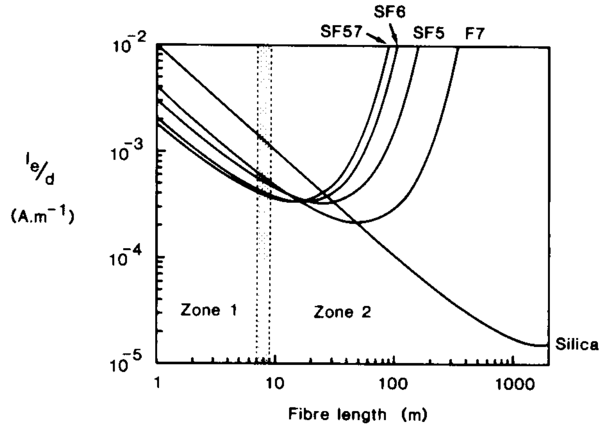

Fig. 1. Noise equivalent current Ie (normalized to coil diameter d) vs fiber length.

The bandwidth of the current sensor is limited by the fact that the instantaneous value of current changes during the time taken for the light to propagate through the fiber coil. The optical rotation θ induced by a sinusoidal current $i = a \sin\omega t$ is given by the integral

$$\theta(\omega) = \int_{t-t_1}^{t} ka \sin\omega t' dt', \quad (6)$$

where t is the time when the light exits the coil, $t_1 = nL/c$ is the optical transit time, and k is a constant relating the optical rotation to the current. Thus

$$\theta(\omega) = 2ka \sin\omega\left(t - \frac{nL}{2c}\right)\frac{1}{\omega}\sin\left(\frac{\omega nL}{2c}\right). \quad (7)$$

Here c is the speed of light and n the fiber core refractive index. The amplitude of the signal varies with frequency as a sinc function, so the system has a low pass response with the 3-dB point at a frequency f_0:

$$f_0 = \frac{1.391c}{\pi nL}. \quad (8)$$

We can now divide Fig. 1 loosely into two zones of operation for the fiber current monitor. The boundary is chosen to be in the region of 7–9 m, giving a bandwidth of ~10 MHz at the divide. Within the high

Table I. Verdet Constant, Attenuation and Refractive Index Values for a Selection of Glasses at a Wavelength of 633 nm

Glass type	Verdet constant V × 10^{-6} (rad · A^{-1})	Attenuation α (dB · km^{-1})	{α/V} × 10^6 (dB · A · rad^{-1} · km^{-1})	Refractive index n
SF59	32.5	4665	143.5	1.943
SF58	30.0	3288	109.6	1.909
SF57	25.2	609	24.2	1.839
SF6	22.3	522	23.4	1.799
SF1	17.2	696	40.5	1.712
SF5	15.0	348	23.2	1.668
SF2	13.9	348	25.0	1.644
F2	12.4	1220	98.4	1.616
F7	11.4[a]	174	15.3	1.622
Germania doped silica	4.5	5	1.1	1.465

[a] Measured value.

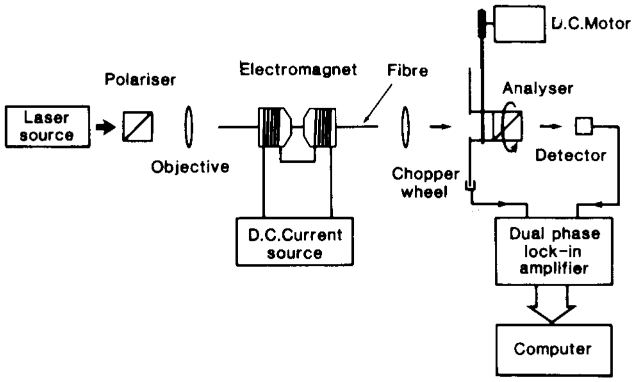

Fig. 2. Experimental configuration for measurement of Verdet constant.

bandwidth region (zone 1) the compound glasses exhibit a better sensitivity than silica, the improvement being by a factor approximately equal to their Verdet constant increase over silica. In zone 2, the current sensitivity is diminished as the losses become dominant for the compound glass fibers. For longer fibers, silica has the greatest current sensitivity but at a much reduced bandwidth. Typically, a 1-MHz bandwidth would result from 88 m of silica fiber.

Of the compound glasses studied, Schott F7 has the best attenuation to Verdet constant ratio and is optimal over a wide range of lengths (from 15 to 50 m). Consequently, it was chosen for a trial fiber fabrication and measurement. A 10-mm diam rod of Schott F2 was used as the cladding glass, and an axial hole of 1-mm diam was ultrasonically bored to accept the F7 core rod. The composite rod was then drawn into a 1-mm core and sleeved with further F2 glass to produce a preform from which a fiber of 160-μm diameter was drawn at a temperature of ~600°C. The fiber was spun during the final draw to eliminate the linear birefringence.[7] The fiber parameters are given in Table II.

The Verdet constant of this fiber was measured using the arrangement[8] shown in Fig. 2. A spun single-mode silica fiber whose characteristics are given in Table II was used as a comparison. Plane-polarized light from the laser source was launched into the fiber, which was mounted so as to minimize the birefringence introduced by stresses and bends. The rotating polarizer assembly was driven at ~2000 rpm and included a chopper wheel to provide a reference signal. A dual-phase lock-in amplifier with computer averaging of the output was used to measure the phase difference between the detector and reference signals. A dc magnetic field was applied over a 2-cm length of the fiber with an electromagnet, and the system was calibrated using a standard silica fiber before measuring the soft glass fiber. Measurements were made at HeNe (633-nm) and laser diode (789-nm) wavelengths, and the results are given in Table II as the fractional increase in the Verdet constant of F7 over silica at both wavelengths. The results agree well with the published data and indicate a 2.5-fold increase in the Verdet constant relative to silica with a minimum attenuation of 470 dB/km.

Analysis of the optimal fiber design for the fiber current sensor reveals a compromise between fiber loss and the value of the Verdet constant. Provided it is permissible with regard to bandwidth considerations to use the optimum fiber length, the sensitivity depends on the ratio of the attenuation to the Verdet constant (α/V). This ratio can be regarded as a figure of merit when assessing the performance of a glass for optimum current sensitivity. Silica has the lowest value and thus the greatest sensitivity.

The situation is different if the fiber length must be limited to obtain a high bandwidth. In this case the optimum choice of glass depends on fiber length. As expected, for short lengths where the attenuation is unimportant, the sensitivity varies as the inverse of the Verdet constant.

Schott F7 glass exhibits a useful combination of low loss and enhanced Verdet constant. A fiber has been fabricated from this glass and measured to have a minimum attenuation of 470 dB/km and a Verdet constant of 2.5 times that of silica. The performance of the fiber is predicted to be superior to silica fibers for all lengths up to 50 m.

Table II. Characteristics of the Fibers Measured

		Silica fiber	Compound glass fiber
Core composition		93 mol% SiO_2	Schott F7
Cladding composition		Silica	Schott F2
Cutoff wavelength		540 nm	600 nm
Numerical aperture		0.14	0.13
Cladding diameter		125 μm	160 μm
Attenuation	633 nm	17 dB · km^{-1}	770 dB · km^{-1}
	789 nm	4 dB · km^{-1}	490 dB · km^{-1}
Spin pitch		20 mm	8 mm
Measured relative Verdet constant	633 nm	1	2.56 ± 7%
	789 nm	1	2.59 ± 9%

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