1/f noise in the extinction coefficient of an optical fibre

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Electronics Letters Online No: 19940917

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1/f noise in the extinction coefficient of an optical fibre

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Indexing terms: Optical fibres, Optical losses, Random noise

The extinction coefficient, used to express losses in optical fibres due to absorption and diffusion, fluctuates in time with a $1/f$ spectrum. The authors have measured fluctuations in the intensity of light propagating through optical fibres. Noise measurements as a function of fibre length show that the noise is not due to fluctuations in reflectivity at the ends. The relative noise in the intensity of the transmitted light is proportional to fibre length.

Introduction: Light propagating through optical fibres is partly absorbed and diffused. This is mainly due to scattering by optical inhomogenities and absorption. The extinction is characterised by the extinction coefficient β. In this parameter, the different loss mechanisms are combined. This Letter shows that the extinction coefficient is not a constant, but fluctuates in time, with a $1/f$ spectrum. Muscha *et al.* have performed experiments with laser light scattered by quartz single crystal [1] and water [2]. They found that the intensity of the scattered laser light fluctuated in time and that the fluctuations had a $1/f$ spectrum.

We investigated intensity fluctuations of light at the output of optical fibres. The spectral density of these intensity fluctuations is closely related to that of the extinction coefficient fluctuations. Our object was to verify whether or not the extinction coefficient fluctuates in time and whether or not the spectral density of the transmitted light is inversely proportional to frequency. Furthermore, we examined the influence of fibre length on the relative noise of the transmitted light.

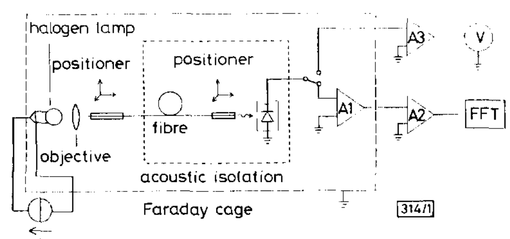

Fig. 1 *Measurement setup for optical fibre experiments*

Experiments: The fibre used in our experiments is a graded index multimode quartz fibre with a core diameter of 50μm and an experimentally obtained attenuation of 16dB/km. Fig. 1 shows the setup used in the experiments. The light source is a halogen lamp. We used a halogen lamp, rather than a laser or an LED, because of the lower noise level. A laser diode [3, 4], as well as a LED, shows $1/f$ noise in the optical output. After a short burn-in period, a stable halogen lamp only shows the inevitable shot noise $2qI$ on the detector, in a frequency range between 1Hz and 100kHz. With the use of a microscope objective, the light is focussed on one end of the fibre. The light intensity at the output of the fibre is monitored with a silicon *pin* photodiode. The photocurrent of this diode is proportional to the light-power incident on its active area. The AC component of the photocurrent is amplified by low-noise current amplifier A1 and low-noise amplifier A2. The signal is measured and processed by an FFT analyser, resulting in a spectrum of the intensity fluctuations. Current amplifier A3 is only used to measure the DC photocurrent accurately.

For comparison, measurements are also taken with a hollow pipe between the halogen lamp and the detector. In this way, the noise generated by the lamp and detector can be measured. Knowledge of this background noise is necessary to verify that the measured noise is actually generated by the optical fibre. Furthermore, if the background noise is not negligible, the results need to be corrected for the background.

Different lengths of fibre were measured, to determine whether the noise is caused by fluctuations in the reflectivity at the fibre end or by the volume of the fibre. To ensure that the properties of the different fibre segments are identical, they are taken from one and the same fibre, with an initial length of 1.4km, that is cut to different lengths. Measurements are taken with fibre lengths of 32, 64, 128, 254 and 512m.

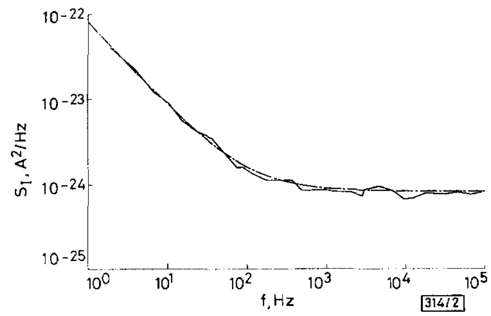

Fig. 2 *Measured noise spectrum with curve fit for 128m fibre*

$I_{ph} = 2.60\mu A$

Results: For each fibre length a number of measurements is taken. The lamp power, and thus the photocurrent, is varied stepwise, and for each photocurrent a spectrum is measured. On these spectra, a curve of the form

$$S_I = S_{shot} + S_{1/f} = 2qI_{ph} + \frac{A}{f} I_{ph}^2 \qquad (1)$$

is fitted. Fig. 2 shows a spectrum and the curve fit. The different values of $f \cdot S_{1/f}$ are plotted against photocurrent I_{ph} in Fig. 3.

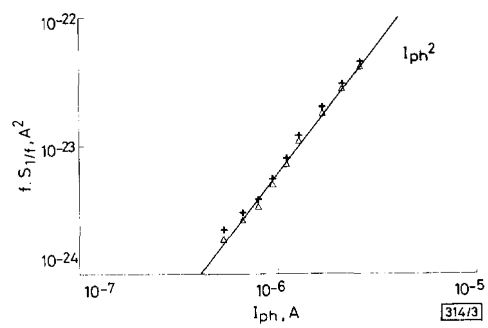

Fig. 3 $f \cdot S_{1/f}$ *against* I_{ph} *for 64m fibre*

+ measured values
Δ corrected for background noise

Because $f \cdot S_{1/f}$, the $1/f$ part of the spectrum at 1Hz, is proportional to I_{ph}^2, a line of slope 2 can be drawn through the experimental values on a plot of $\log f \cdot S_{1/f}$ against I_{ph}^2. On this line, the relative noise $f \cdot S_{1/f}/I_{ph}^2$ is constant. Considering the relative noise makes the results independent of the light intensity used in the experiment. The noise is corrected by subtracting the background noise, which is roughly $f \cdot S_{1/f}/I_{ph}^2 = 7 \times 10^{-13}$, whereas the corrected relative noise is between 10^{-12} and 3×10^{-11}. In Fig. 4 relative noise is plotted against fibre length together with a line of slope 1.

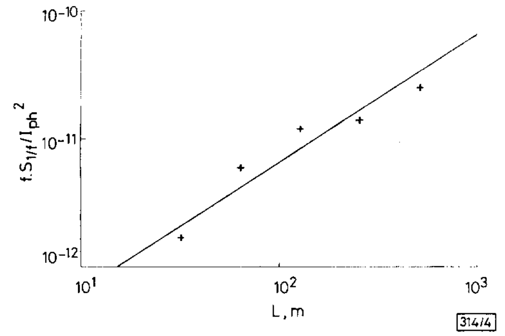

Fig. 4 *Relative 1/f noise $f \cdot S_{1/f}/I_{ph}^2$ against fibre length L*

Discussion: Fig. 4 demonstrates that the log of relative noise in light intensity is proportional to fibre length. This can be described by a model based on a noise source distributed in the bulk of the fibre, and not at the ends. The relation between the light power entering the optical fibre and the output power is

$$P(L) = P(0)\exp(-\beta L) \qquad (2)$$

where $P(0)$ and $P(L)$ are the light power at the front and end of the fibre, respectively. β is the extinction coefficient ($3.7 \times 10^{-3}\text{m}^{-1}$), and L the length of the fibre.

The relation for the noise is derived from the relation between the normalised fluctuations

$$\frac{\Delta P_o}{P_o} = -\beta L \frac{\Delta\beta}{\beta} \Rightarrow \frac{S_{P_o}}{P_o^2} = \beta^2 L^2 \frac{S_\beta}{\beta^2} \qquad (3)$$

Here, S_{P_o} and S_β are the spectral noise densities of power and extinction coefficient fluctuations, respectively. Vandamme and de Boer [3] have already proposed that the relative noise in the extinction coefficient, for the optical active region of a laser diode, has the form

$$\frac{S_\beta}{\beta^2} \propto \frac{\varepsilon}{f\Omega} \qquad (4)$$

With ε a $1/f$ noise parameter, f the frequency and Ω the volume of optical active area. Here we propose

$$\frac{S_\beta}{\beta^2} = \frac{\varepsilon}{fM} \qquad (5)$$

with M the number of scatterers proportional to fibre length, $M = mL$, with m the number of scatterers per length unit. From eqns. 4 and 5 the relative $1/f$ noise in the output power is

$$\frac{S_{P_o}}{P_o^2} = \beta^2 L \frac{\varepsilon}{fm} \qquad (6)$$

Hence, the relative $1/f$ noise in the output light intensity, is proportional to fibre length (Fig. 4). This Figure shows that the relation between noise and fibre length is

$$\frac{S_I}{I_{ph}^2} = KL\frac{1}{f} \qquad (7)$$

with $K = 7 \times 10^{-13}\text{m}^{-1}$.

Conclusion: Measurements of the intensity of light propagating through optical fibres showed fluctuations in time. Comparing measurements with a hollow pipe proved that the fluctuations originate in the fibre. The fluctuations in light intensity are caused by fluctuations in the extinction coefficient β, and not by fluctuations in the reflectivity at the ends of the fibre. The spectral density of the fluctuations is inversely proportional to frequency.

The relative noise in the light intensity at the output of an optical fibre is proportional to the length of the fibre. The model presented in this Letter gives a qualitative explanation of this dependence.

Acknowledgment: We thank W. van Etten for providing the optical fibre.

26 May 1994
Electronics Letters Online No: 19940867

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Efficiency and thermal behaviour of cerium-doped fluorozirconate glass fibre Bragg gratings

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Indexing terms: Flouride glasses, Gratings in fibres

1.55μm Bragg gratings have been written in cerium-doped fluorozirconate glass singlemode fibres through UV illumination at 246nm. Photoinduced refractive index changes up to 4×10^{-4} have been achieved, leading to grating efficiencies close to 100%. Preliminary results on the thermal behaviour of the gratings and realisation of a tunable laser including such a grating are also reported.

Introduction: The potential applications of gratings directly written in photosensitive optical fibres has strongly stimulated research in this area, and a significant amount of work has been carried out over the past few years to enhance the UV sensitivity of silica based fibres [1–3]. The first observation of UV induced permanent gratings in ZrF_4 based glasses doped with cerium ions was recently reported [4]. Among the ZrF_4 or HfF_4 based glasses, the ZBLALi (ZrF_4-BaF_2-LaF_3-AlF_3-LiF) glass composition was shown to be the most efficient. We report in this Letter the influence of the cerium concentration on the photosensitivity of ZBLALi fibres, and present the resulting improvements in the photoinduced refractive index changes. We also give preliminary measurements on the grating thermal stability. A tunable fibre laser has been fabricated for illustration.

Experiment: The singlemode fibres used in these experiments were drawn from preforms prepared with conventional techniques, with a ZBLALi:Ce^{3+}-ZBLANY core-cladding glass structure. The numerical aperture was 0.22, the core diameters varied between 2.5 and 4μm, and the cerium concentrations between 1 and 5wt%. Owing to their tendancy to crystallise, the core glasses containing more than 3wt% cerium required higher quenching rates when making the preforms.

The gratings were created with a transverse holographic method using a mirror to produce the fringe pattern. UV exposure was performed at room temperature, with a pump wavelength of 246nm, fluences per pulse of 60 – 500mJ/cm² on the sample, and the Bragg resonance wavelengths were tuned near 1.55μm. The saturated grating reflectivity R was determined from the fibre transmission spectrum recorded one day after the writing. The saturated index modulation Δn deduced from $R = \tanh^2(\pi\Delta n\eta(V)L/$