1/f noise as a diagnostic tool, and 1/f noise in the extinction coefficient of optical fibres

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Foreword

This report consists of two parts. Part I gives an account of the work, done in the beginning of my final project. Here, resistance noise measurements are proposed, as a diagnostic tool to detect defects in thin film resistors, and Al interconnects. Advantages of this method are, that it is fast, non-destructive, and more sensitive than resistance measurements. Part I has been sent in for publication, to IEEE Transactions on Reliability.

Part II covers our research into 1/f noise in optical fibres, the main part of my final project. Scattering and absorption cause losses of light in optical fibres, that can be expressed with an extinction coefficient. To investigate fluctuations in the extinction coefficient, I measured fluctuations in the transmitted light. The observed noise in the transmitted light has a 1/f spectrum. A model, describes the relative noise in the transmitted light power, as a function of fibre length. Experimental results from optical fibres of different lengths, are in agreement with the presented model, and demonstrate that the noise is originating in the fibre, and is not due to fluctuations in the light source, the detector or reflectivity at the ends of the fibre.

Our results have been sent to Electronics Letters, and is added as an appendix to part II.

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Part I

Resistance noise measurement, a better diagnostic tool to detect stress and current induced degradation

RESISTANCE NOISE MEASUREMENT
A BETTER DIAGNOSTIC TOOL TO DETECT STRESS AND
CURRENT INDUCED DEGRADATION

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Key Words **- 1/f Noise, Thin film resistors, Interconnects, Degradation, Electromigration.**

Reader Aids **-**
Purpose: Present a new model
Special math needed for derivations: None
Special math needed to use results: None
Results useful to: Reliability engineers

Summary & Conclusions **- Early degradation by holes or kinks in thin film resistances is studied by 1/f noise measurements. A model describing the increase in 1/f noise and resistance due to damages is presented. Our calculations are in agreement with experimental results and show quantitatively that 1/f noise is a more sensitive parameter than resistance measurements only. Noise measurement can be used as a fast and non destructive technique for reliability testing of LSI Al interconnects and thin film resistors.**

1 INTRODUCTION

Resistometric methods are well known to detect stress and current-induced degradation in thin narrow conducting films or interconnects. Observing 1/f noise, however, is a more sensitive technique to investigate quality and reliability of electronic components. The increase in 1/f noise, caused by a higher local current density around damages, is significantly stronger than the increase in resistance. We have developed a simple model for the calculation of the relative increase in 1/f noise and resistance and have compared these calculations with experimental results.

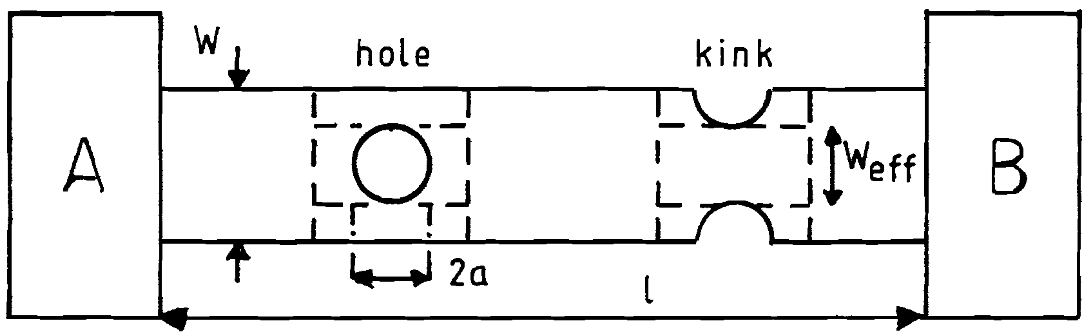

Fig. 1. Geometry of a resistor with a hole and a kink.

2 MODEL

We consider long narrow film resistors, degraded by holes or kinks, shown schematically in Fig. 1. The general equations for resistance R and 1/f noise in resistance S_R due to conductivity fluctuations are [1,2]

$$R = [1/I^2]\int \rho J^2 dA \tag{1}$$

$$S_R = [1/I^4]\int [\alpha \rho^2/nf] J^4 dA = [1/I^4]\int C_{us}\rho^2 J^4 dA/f \tag{2}$$

where $\rho(\Omega)$ is the sheet resistance; J (A/m) the two dimensional current density; dA (m^2) an area element; n (m^{-2}) the free charge carrier concentration; α a dimensionless 1/f noise parameter and C_{us} (m^2) the characteristic 1/f noise for a unit area [3,4].
We approximate the increased local current density around a hole or kink by $J = I/W_{eff}$ over a length W with $W_{eff} = W\text{-}2a$. The current density in the undamaged parts is $J = I/W$. The number of holes or kinks is k. To simplify the calculations we assume all holes or kinks have the same dimensions. The resistance of the k damaged parts then becomes $R_d = k\rho W/W_{eff}$.

The total resistance of the undamaged parts is $R_u = \rho(L-kW)/W$. The resistance of the entire sample becomes

$$R = R_u + R_d = \frac{\rho L}{W}\left[1 + \frac{kW}{L}\left(\frac{W}{W_{eff}} - 1\right)\right] \tag{3}$$

The resistance R_0 of the undamaged sample is $R_0 = \rho L/W$, hence the ratio R/R_0 becomes

$$R/R_0 = 1 + \frac{kW}{L}\left(\frac{W}{W_{eff}} - 1\right) \tag{4}$$

The same approximations applied to eq. (2) leads for the resistance noise in the k degraded parts to

$$S_{R_d} = R_d^2 C_{us}/fkWW_{eff} \tag{5}$$

and in the undamaged parts to

$$S_{R_u} = R_u^2 C_{us}/fW(L-kW) \tag{6}$$

respectively. Resistance noise in the different parts is uncorrelated hence the total resistance noise density S_R is the sum of eqs. (5) and (6).

$$S_R = \frac{\rho^2 C_{us}}{f}\left[\frac{kW}{W_{eff}^3} + \frac{L-kW}{W^3}\right] \tag{7}$$

Resistance noise of a failure free sample is $S_{R0} = R_0^2 C_{us}/fWL$. The ratio S_R/S_{R0} shows the increase in resistance noise

$$S_R/S_{R_0} = 1 + \frac{kW}{L}\left[\left(\frac{W}{W_{eff}}\right)^3 - 1\right] \tag{8}$$

Equations (4) and (8) are functions of W/L, W/W_{eff} and k, and the third power in (8) shows the stronger increase in noise than in resistance due to holes or kinks. For k is larger than 1, the resistor can be considered as k resistors in series of length L/k and degraded by one hole or kink each. One subsection with length L/k, or k subsections in series all have the same R/R_0 and S_R/S_{R0} as the total resistor.

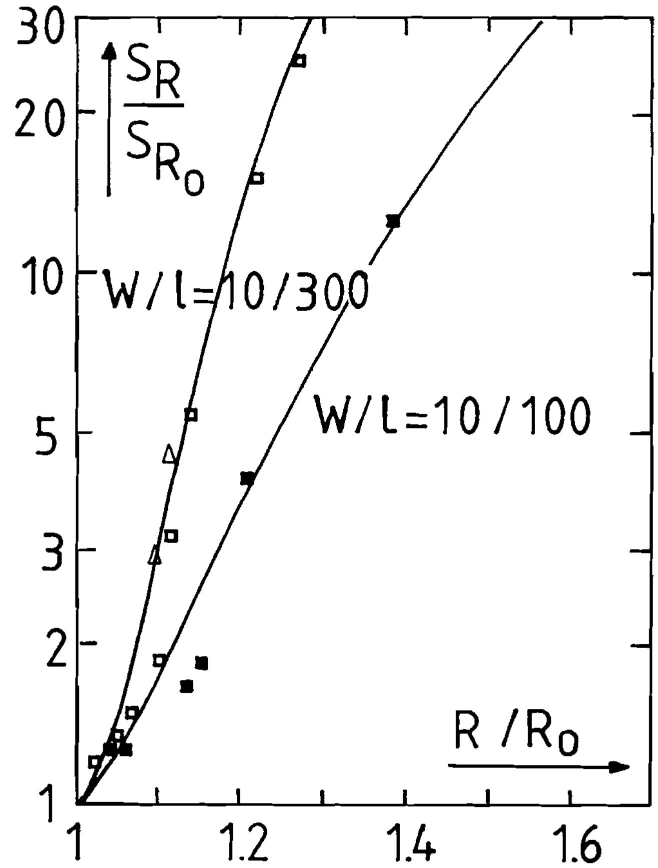

Fig. 2. Relative increase in 1/f noise versus relative increase in resistance due to one hole or kink. Full lines are calculated from eqs. (4) and (8). Experimental results with a hole: W/L = 10/100 ■; W/L = 10/300 □; and with a kink: W/L = 10/300 ▲.

3 EXPERIMENTS AND RESULTS

To verify equations (4) and (8), experiments with decreasing W_{eff} as well as experiments with increasing k are performed. Carbon film resistors with various W/L ratios are used.

First, experiments on samples degraded by one hole or kink are performed. Before degradation we started by measuring the reference values R_0 and S_{R0} of the undamaged resistor. After the first damage is made, R and S_R are measured. This process is repeated after each subsequent enlargening of the hole or kink.

The calculated and experimentally observed relative increase in noise versus a relative increase in resistance for decreasing W_{eff} is presented in Fig. 2. The full lines are calculated for W/L values of 10/100 and 10/300 from eqs. (4) and (8) with k=1. The squares represent the experimental results obtained from 2 resistors with one hole with increasing hole diameter, with different W/L ratios.

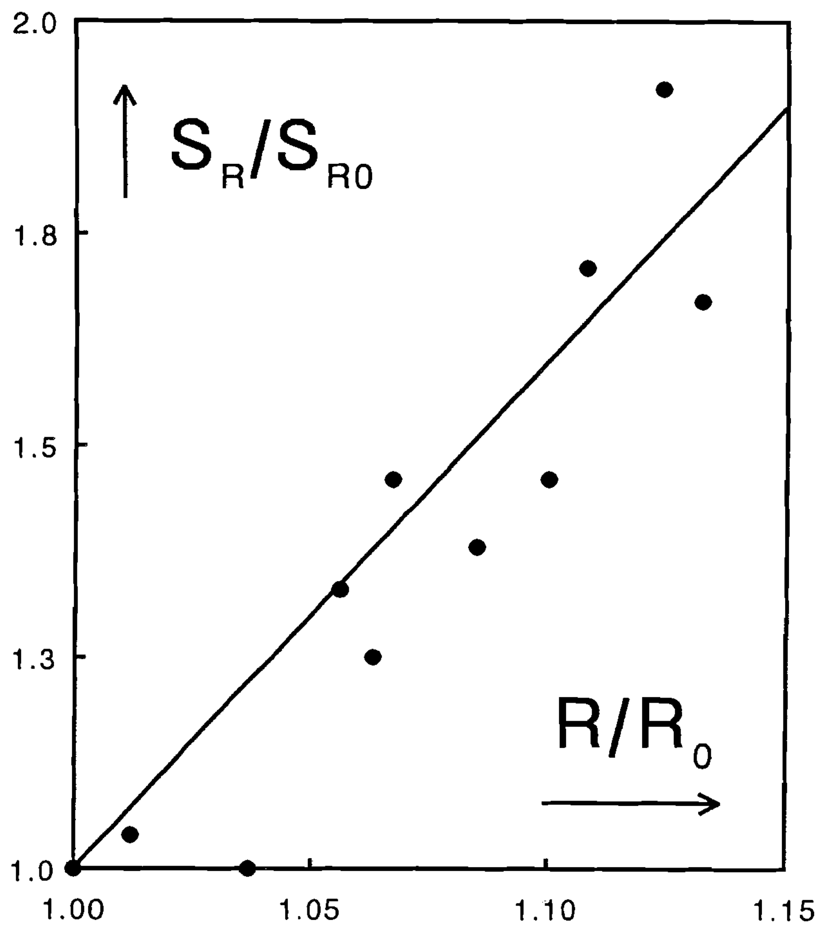

Fig. 3. Relative increase in 1/f noise versus relative increase in resistance due to an increasing number of holes.

The triangles stem from a third sample with an W/L=10/300 degraded by an increasing kink.

Second, the experiment with increasing k is performed on a carbon film resistor with a W/L ratio of 5/563. Again first R_0 and S_{R0} are measured and this is repeated for each additional hole. Measurements are taken for one up to ten holes. All holes have the same diameter and are distributed equidistant over the length of the resistor, with 2a/W=0.46.

Fig. 3 shows the relative increase in noise versus the relative increase in resistance for increasing number of holes k. The full line is calculated with eqs. (4) and (8) with $W/W_{eff}=1.85$.

4 DISCUSSION

Experimental results are in good agreement with model calculations. A quantitative explanation shows why resistance noise measurements are more sensitive than resistance measurements only. The relative increase in 1/f noise is a complementary technique rather than competing with classic failure analysis tests and is applicable to LSI Al interconnects and thin film resistors.

We must stress, however, that eq. (8) only takes into account the increase in noise intensity due to current density increase around the holes or kinks. If the microstructure around these damages is affected, the noise intensity will be higher and eq. (8) is no longer valid. Catastrophic increase in noise over more than a few decades for only a few percent of increase in resistance are due to microscopic changes in the structure and not due to a simple increase of current density around a hole in the conducting path.

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Part II

1/f Noise in the extinction coefficient of optical fibres

1 Introduction

Light propagating through optical fibres is partly lost. This is mainly due to scattering on optical inhomogenities[1] and absorption. The extinction is characterized by the extinction coefficient ß. In this parameter, the different loss mechanisms are combined.

We found, that the extinction coefficient is not a constant, but fluctuates in time, with a 1/f spectrum. Muscha et al. have done experiments with laser light scattered by quartz single crystal[2] and water[3]. 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 the fluctuations in the transmitted light 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. A model describing the length dependence of the noise is also formulated.

2 Model

Here, a model will be derived that describes the noise, caused by fluctuations of the extinction coefficient of the fibre, as a function of fibre length. The relation between the power of the light entering the fibre, and the power of the light at the end of the fibre is

$$P(L) = P(0)\exp(-\beta L) \tag{1}$$

where P(0) is the light power at the begin facet of the fibre, P(L) the light power at the end facet of the fibre, L is the fibre length [m], and ß is the extinction coefficient which has an experimentally obtained value of $3.7*10^{-3}m^{-1}$ (see fig.1). The fluctuations in the output light power, due to fluctuations in the extinction coefficient, are given by:

$$\Delta P(L) = \frac{\partial P(L)}{\partial \beta}\Delta\beta = -\beta L\frac{\Delta\beta}{\beta}P(L) \qquad (2)$$

From the relation between the normalized fluctuations, follows the relation for the noise:

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

Here $S_{P(L)}$ and S_β are the spectral noise intensities of power and extinction coefficient fluctuations, respectively. The relative noise in the extinction coefficient S_β/β^2 has a form similar to the expression for the noise in the extinction coefficient for the optical active region of a laser diode, as has been proposed by Vandamme and de Boer[4].

$$\frac{S_\beta}{\beta^2} = \frac{\varepsilon}{fM} \qquad (4)$$

Here ε is a 1/f noise parameter and M the number of scatterers. M is proportional to fibre length:

$$M = mL \qquad (5)$$

where m is the number of scatterers per length unit. From (3), (4) and (5) follows for the relative 1/f noise in the output power:

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

Hence the relative 1/f noise in the output light intensity, is proportional to fibre length.

The forementioned value of β is extracted from figure 1, which shows $2*\ln(V_L)$ as a function of fibre length L, for constant I_{ph}. The slope of the drawn line is equal to β, as can be seen from the following derivation. Assumed is that

$$P(0) \propto \frac{V_L^2}{R_L} \quad and \quad P(L) = CI_{ph} \qquad (7)$$

where V_L is the voltage across the halogen lamp, R_L the resistance of the lamp, and C a constant. In that case eq. (1) can be written in the form

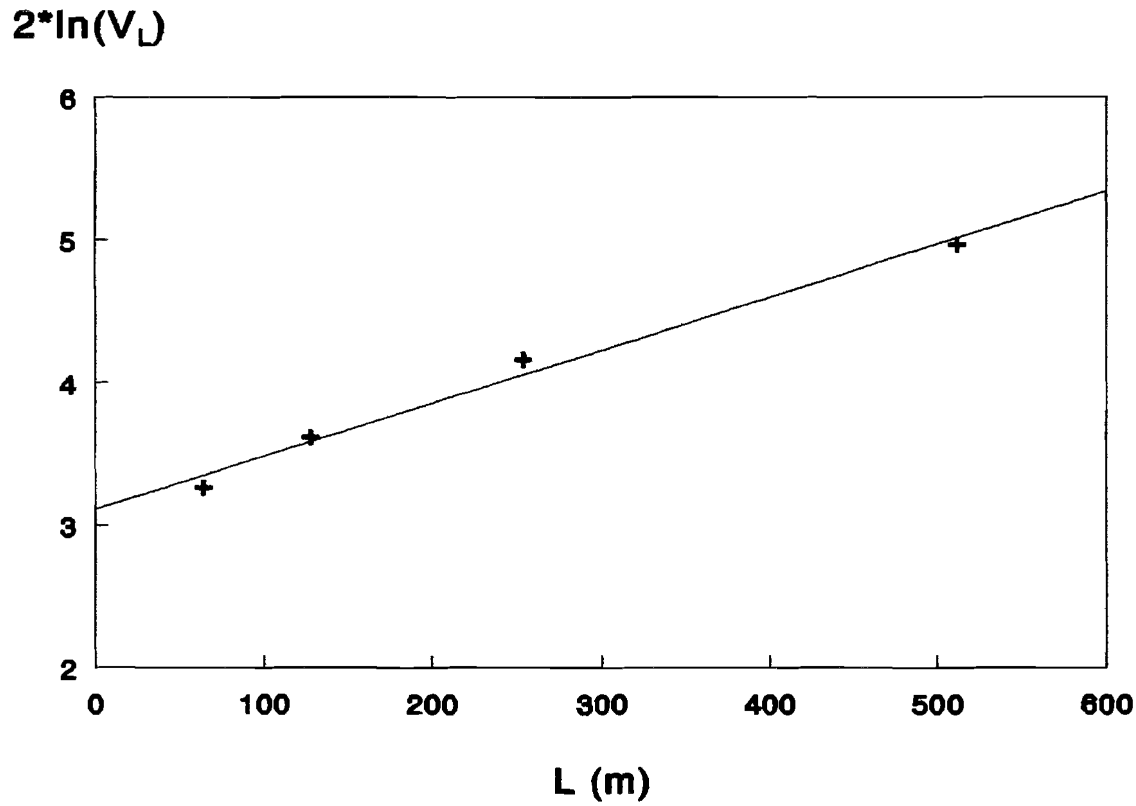


Figure 1 : $2*\ln(V_L)$ as a function of fibre length for constant I_{ph}; $I_{ph}=0.79\mu A$.

$$\ln(CI_{ph}) = \ln F + 2\ln V_L - \ln R_L - \beta L \tag{8}$$

Here, F is the fraction of the power dissipated in the halogen lamp, that is converted into visible light and is coupled into the fibre. From eq. (8) can be seen that for constant I_{ph}, and assuming R_L and F are constant, $2*\ln(V_L)$ is proportional to L with slope ß. This results in a ß of $3.7 \cdot 10^{-3} m^{-1}$, which is equal to an attenuation of 16 dB/km.

Most light rays, however, do not propagate parallel with the fibre's axis, and thus their pathlength is somewhat larger than the fibre length. To calculate the magnitude of this difference, we first have to consider the properties of the fibre. The fibre, that we used in our measurements, is a graded index multimode fibre with a parabolic refractive index profile, and a core diameter of 50 μm. The cladding layer consists of pure quartz which has a refractive index of $n_{cl} = 1.46$. The refractive index at the center of the core is at most 1% higher, thus $n_{c0} \leq 1.4746$. In this case the fibre is termed weakly guiding.The pathlength L_p of a ray is then given by[5]

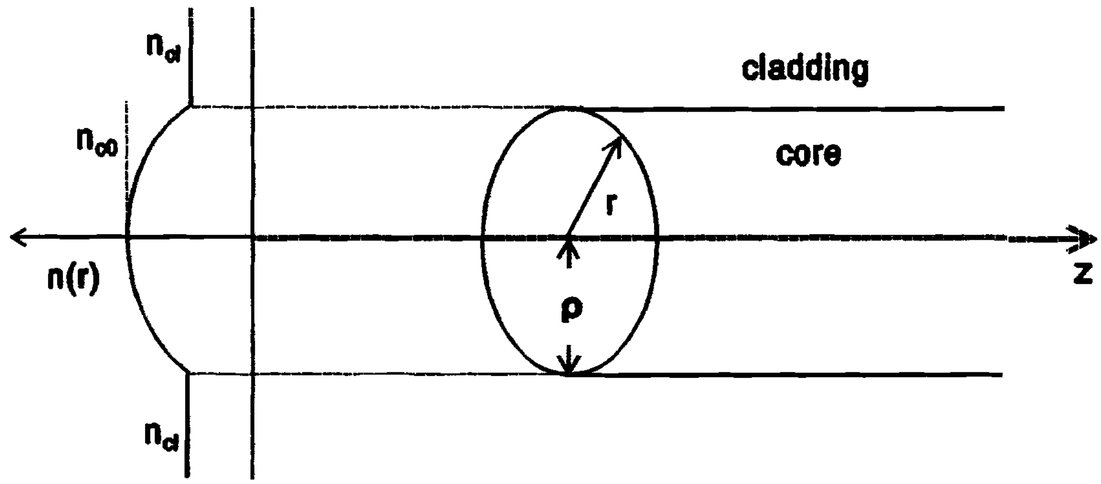


Figure 2 : Profile and nomenclature of a circular graded index fibre. The z-axis lies along the fibre axis.

$$L_p = \frac{L}{4}\left\{ \frac{3n_{co}}{\bar{\beta}} + \frac{\bar{\beta}}{n_{co}} \right\} \tag{9}$$

where L is the fibre length and $\bar{\beta}$ the so-called ray invariant, a parameter that depends on the angle between the ray path and the fibre's axis. For a given ray path, the ray invariant is constant. For bound rays, the ray invariant can take on the values:

$$n_{cl} < \bar{\beta} \le n_{c0} \tag{10}$$

With eq. (9) we can now calculate the minimum and maximum ray pathlength. For $\bar{\beta} = n_{c0}$, pathlength L_p is equal to fibre length (ray parallel with fibre's axis). For $\bar{\beta} = n_{cl}$, we find the maximum boundary for the pathlength:

$$L_p = 1.005L \tag{11}$$

From this, we can conclude that the difference between pathlength and fibre length is negligible, and we can use actual fibre length in eq. (6).

3 Measurement set-up

3.1 Introduction

A set-up is needed, that can measure the spectral density, of noise due to fluctuations in light intensity. Therefore, we must convert the optical signal into an electrical signal. This is done with a PIN photodiode. The photocurrent of this device, is proportional to the intensity of the light, incident on the active area of the diode.

In §3.2, the set-up for measurements carried out on optical fibres is described. To distinguish the noise due to the fibre, from noise generated by other components in the set-up, the background noise has to be measured. The set-up is described in §3.3.

3.2 Optical fibre measurements

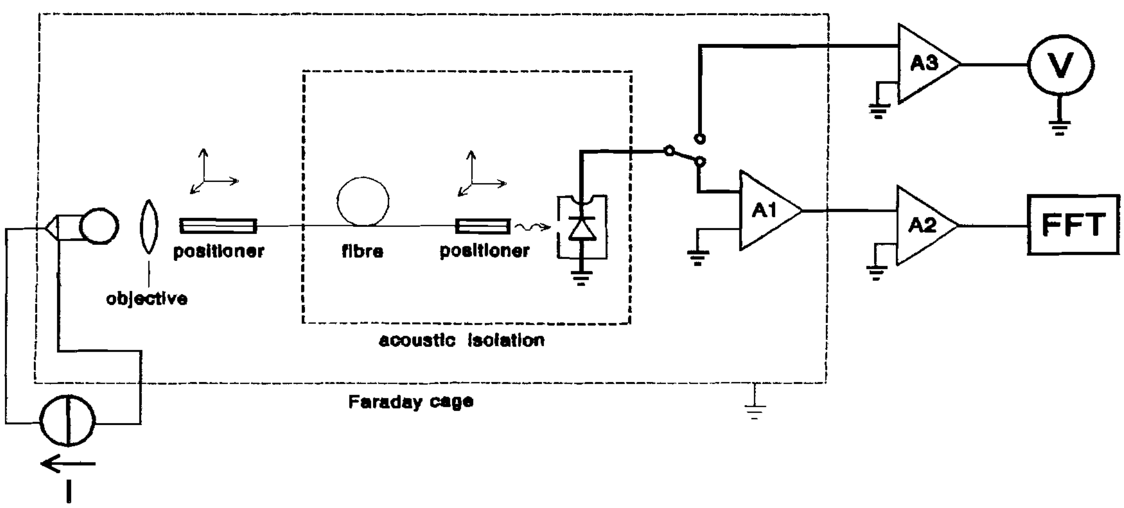


Figure 3 : Measurement set-up for optical fibre experiments.

The measurement set-up is shown in fig. 3. As a light source for the measurements, a halogen lamp was used. We chose a halogen lamp rather than a laser source, because the 1/f noise level of a laser source is higher than the 1/f noise level of a halogen lamp and detector. This is a trade-off, between the optical performance of a laser, and the noise level of the lamp.

The lamp (35W/12V) is supplied with a constant current. It is placed in a metal box on which radiators are fixed providing a heatsink. The light shining through a hole in the lampcase is focussed on one end of the fibre by a microscope objective (magnification 10X, numerical aperture 0.25). The fibre can be positioned so that the light power coupled into the fibre is optimal. The positioner is a Newport F-915T multimode fibre coupler with an FPH-DJ fibre chuck and an FPH-SR strain relief. The strain relief prevents motion of the bare fibre without introducing microbending.

The other end of the fibre is clamped in a self designed chuck. This chuck is held by a three dimensional micropositioner. With this the fibre end can be positioned in order to optimize the light intensity, incident on the active area of the detector. Both ends of the fibre are cleaved, and checked under the microscope.

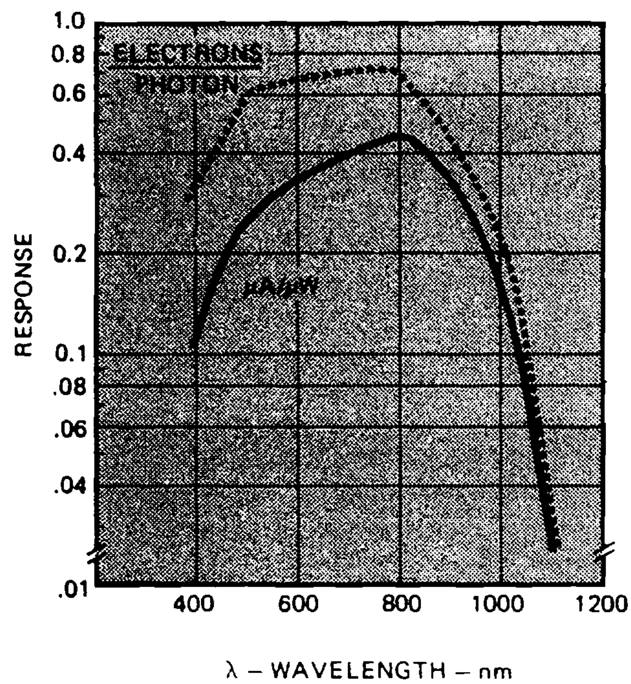


Figure 4 : Spectral response of the HP 5082-4203 PIN photodiode.

The detector is an HP 5082-4203 silicon planar PIN photodiode. The spectral response of this photodiode is shown in fig. 4. The photocurrent of the detector can either be switched to low-noise current preamplifier A3 (Stanford SR570), which is connected to a voltmeter, used to read the DC photocurrent. It can also be switched to the low noise current preamplifier A1 (Brookdeal 5002). The signal coming from A1 is, again, amplified by low noise amplifier A2 (Brookdeal 9453). The signal is analyzed with an HP 35665A FFT dynamic signal analyzer. The thin dotted lines depict Faraday cages in which the set-up is put.

The inner cage is covered on the inside with acoustic isolating material, in order to shield the fibre from acoustic and mechanical vibrations and temperature fluctuations. The suppression of the microphonic effect is absolutely necessary since the set-up is extremely sensitive to vibrations. These vibrations cause spikes, peaks and bulges, hiding the 1/f spectrum. The part of the set-up where the light is coupled into the fibre, is also very sensitive to vibrations. Therefore, the lamp with its radiators and the positioning equipment, are immovably fixed to a metal plate that is placed on top of shock absorbing material. The weight of the whole, in combination with the damping material, provides a mechanical low pass filter. Over the lamp and the positioning equipment, a dust cap is placed because dust will cause additional scattering.

It is also important that the lamp is fixed immovably to the lampcase, as well as the fibre must be clamped immovably in the chuck, and the chuck must be fixed immovably in the positioner. Any mechanical drift will cause drift in the photocurrent. In that case, $1/f^2$ noise that is generated by the current drift will exceed 1/f noise at low frequencies. This problem was often met.

3.3 Background noise measurements

Another set-up was used, in order to verify that the 1/f noise was indeed generated by the fibre, and was not coming from the halogen lamp or the detector. This set-up is shown in fig. 5. The lamp box is connected to the detector box by a hollow plastic pipe. Due to the pipe, the detector and lamp are immovable with respect to each other, and it keeps dust and background light away. The pipe is made of a non-heatconducting plastic, in order to prevent the detector from heating by conduction via the pipe, as the lamp box can get very hot.

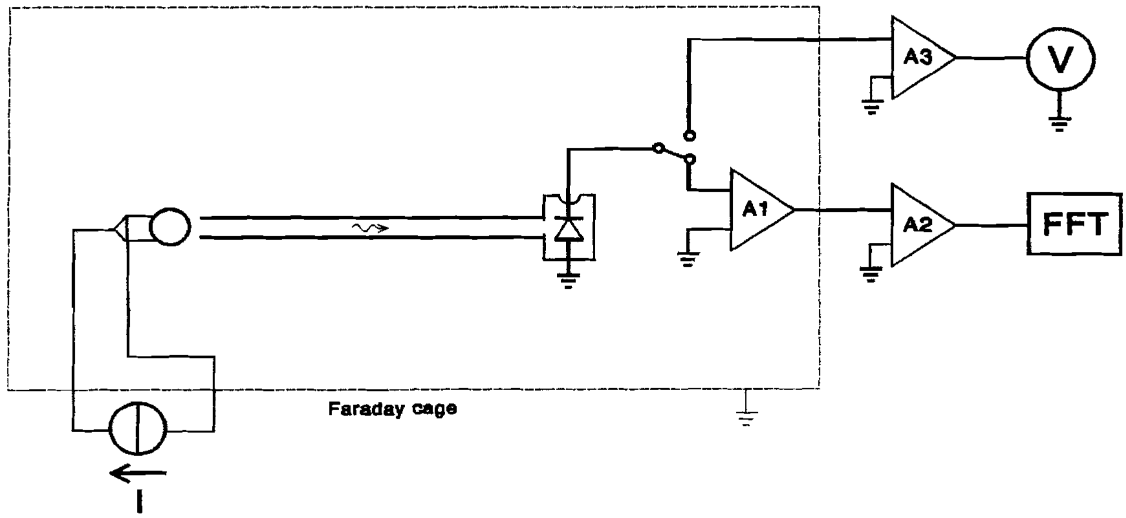


Figure 5 : Set-up for background noise measurements.

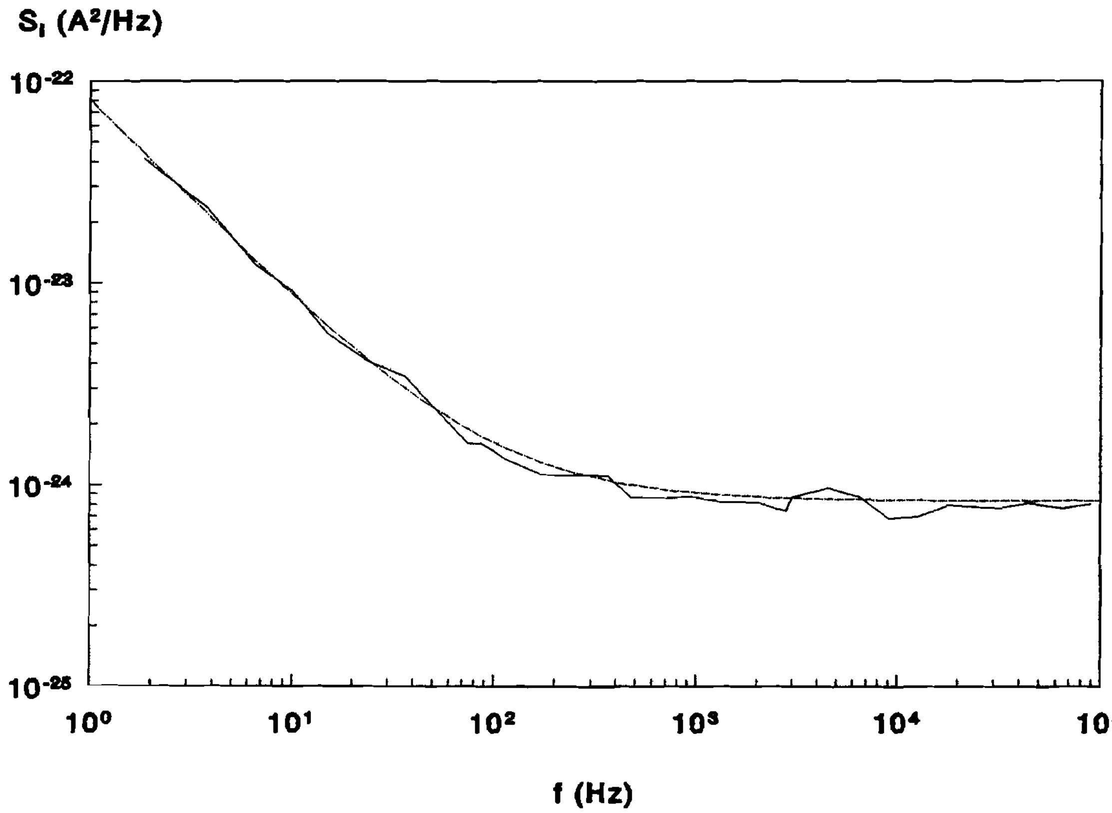


Figure 6 : Measured noise spectrum with curve fit for the 128m fibre. I_{ph} = 2.60 μA.

4 Data processing

Here will be described how the data, in the form of numerous measured spectra, will be processed in order to obtain a characteristic of 1/f noise intensity versus fibre length. For a given fibre length, noise spectra will be measured for different photocurrent values I_{ph}. Then each measured spectrum is transferred to a PC. The spectra are the sum of only two noise components, 1/f and shot noise. To determine the actual 1/f noise level a curve of the form

$$S_I = S_{shot} + S_{1/f} = 2qI_{ph} + \frac{A}{f}I_{ph}^2 \qquad (12)$$

is fitted on the spectrum as shown in fig. 6. The dotted line represents the curve fit. For each fibre length, a plot of $f*S_{1/f}$ versus I_{ph} is made. The spectra are measured for fixed I_{ph} values.

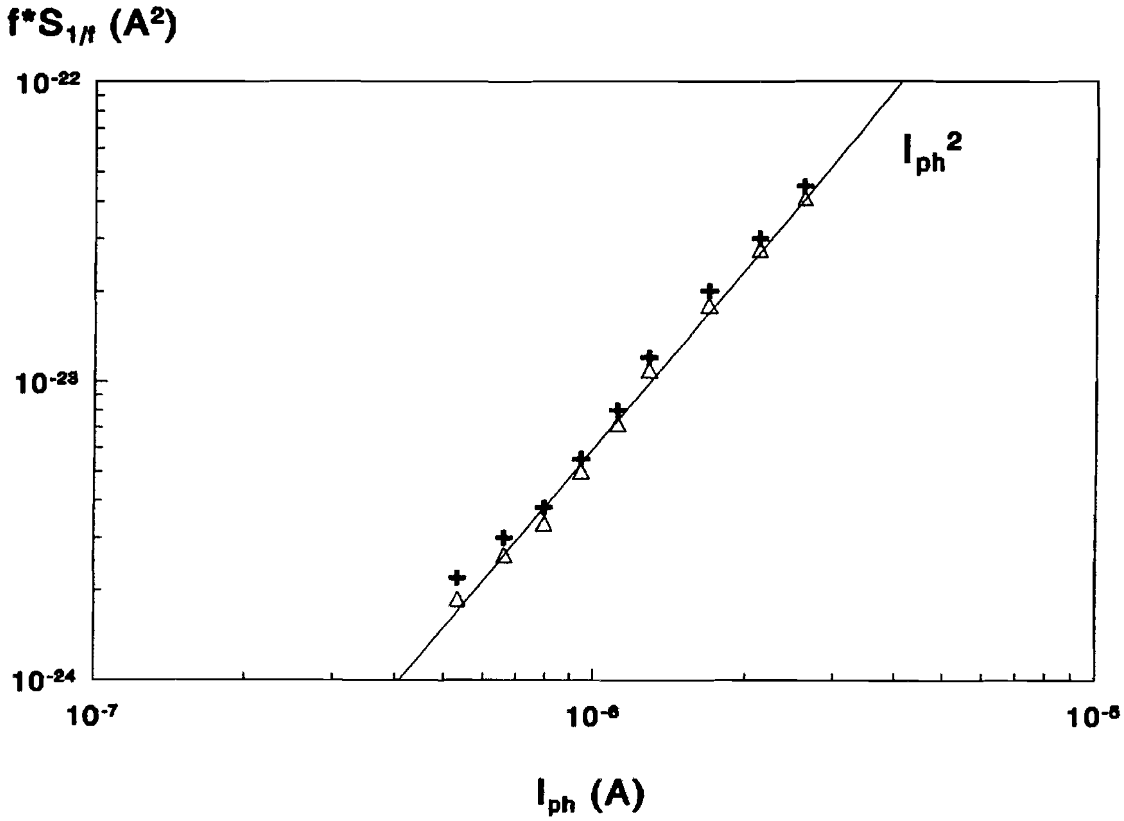


Figure 7 : **Plot of $S_{I,1/f}f$ versus I_{ph} for the 64m fibre.**
+ = measured values; △ = corrected for background noise

These values correspond with a set of values for which the background 1/f noise is measured, generated by other components in the set-up (see §5.2). The measured values $f^*S_{1/f}$ of the background noise are subtracted from the $f^*S_{1/f}$ values stemming from the fibre measurements, thus correcting them for background noise.

Since $S_{P(L)}$ is proportional to $P(L)^2$ as shown in eq.(3) and I_{ph} is proportional to P(L), $f^*S_{1/f}$ is proportional to I_{ph}^2. Now, on a plot of log $f^*S_{1/f}$ versus log I_{ph}, a straight line of slope 2 is drawn that fits the points. An example of such a plot is shown in fig. 7. Each fibre length has a different value for the normalized relative fluctuations $f^*S_{1/f}/I_{ph}^2$. These values are plotted versus fibre length, thus giving a relation between the relative 1/f noise intensity and fibre length.

5 Measurements and results

5.1 Initial difficulties

Our first object was to investigate whether or not optical fibres cause 1/f noise in the intensity of light propagating through the fibre. We succeeded in that, already in an early stage. Good 1/f spectra were measured for two NKF multimode fibres (1.04m and 3.65m) and a CANSTAR multimode fibre (1.95m). The measurements, however, were not sufficient to prove a proportionality with length since we had only three lengths of fibre, one of them being of a different type.

A second problem was that the reproducibility of the measurements was poor. Differences in measured noise intensity $S_{1/f}/I_{ph}^2$ amounted to a factor 4 for identical measurements taken on different occasions. This was, as would appear later, to a large extent, due to the connection between the lamp box and the fibre that we used at that time. In contrast to what is shown in fig. 3, the fibre, then, was cemented in a standard fibre chuck with screw-on fitting, and there was no objective between the lamp and the polished fibre tip. This screw-on fitting had some backlash which could alter the position of the fibre with respect to the lamp.

In order to verify the dependence of the light intensity noise on fibre length, we need to perform measurements on identical fibres of different lengths. Since we had a fibre of about 1.5km, we could make several fibre lengths that had identical properties. The measurements were redone with these fibres. For the first measurement, a fibre of 1024m was used. When the measurement was done, the fibre was cut in half and thus the next measurement was done with a fibre of half the original length. This was done repeatedly, down to a length of 32m. The fibre half at the lamp side, was always kept in the standard chuck, while the end that was cut, was placed in the home made fibre holder. This was done, to keep in-coupling conditions as constant as possible. Again the measured spectra showed 1/f noise , and the noise level was proportional to I_{ph}^2.

Reproducibility, however, was still poor and a proper length dependence was not visible. To optimize the coupling of the light into the fibre, the set-up was improved by a chuck, in combination with a three dimensional micropositioner and an objective holder. With this, and a microscope objective, the measurement set-up becomes as shown in fig. 3.

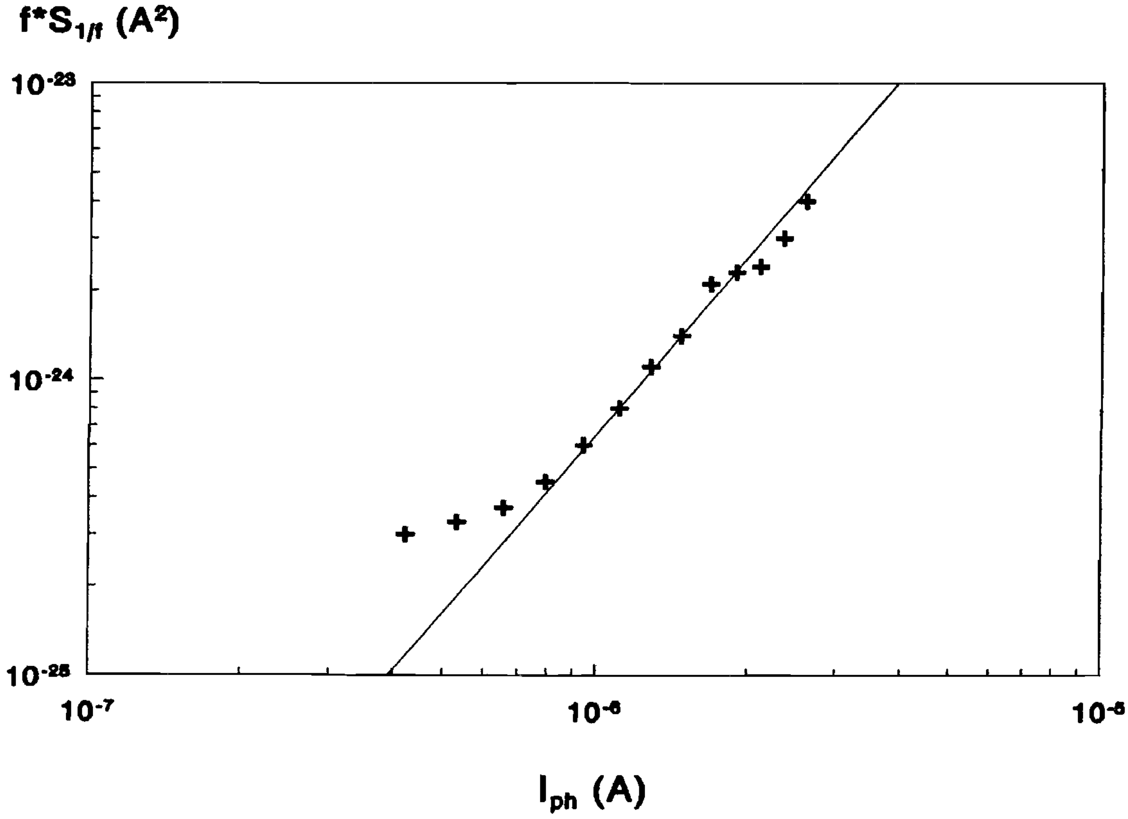
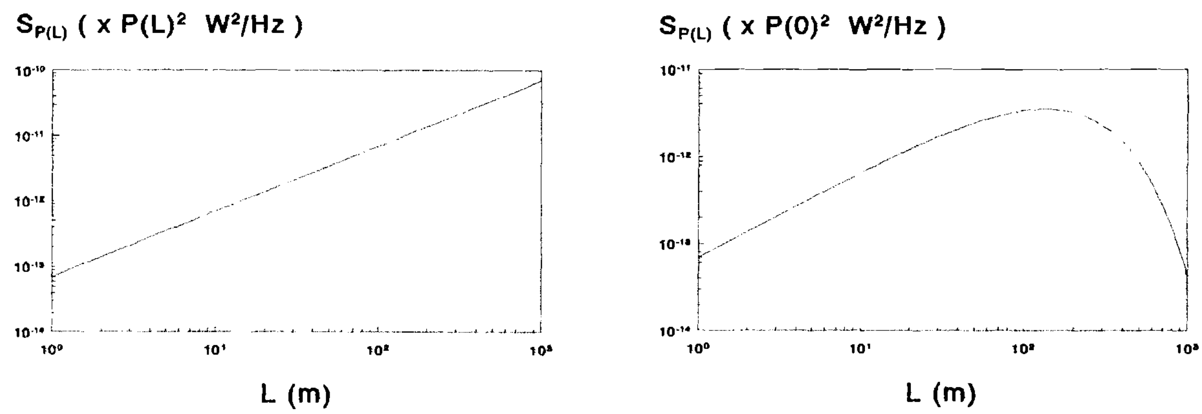


Figure 8 : **Background noise $fS_{1/f}$ plotted versus I_{ph}.**

5.2 Background noise measurements

Before discussing the results of the measurements with the improved set-up it has to be verified that the measured 1/f noise is generated by the fibre, and not by other components like the detector or the lamp. The measurement set-up used for this verification is shown in fig. 5 and described in §3.3. In earlier measurements with this set-up, we found that the noise generated by the other components (background noise) was negligible compared to the noise measured on the NKF and CANSTAR fibres. However, the noise intensity measured on the fibre lengths originating from the 1.5km fibre, is of a lower level. Consequently, for short fibres, the background noise cannot be neglected and measured noise intensities need to be corrected for this background noise. Therefore, the background noise as a function of photocurrent was measured in the current range of interest. The results are shown in fig. 8.

The background noise is proportional to I_{ph}^2, except for lower currents. For these lower currents, however, 1/f noise is hardly exceeding the shot noise of the detector, so here, deviations can be relatively large. Since the noise is proportional to I_{ph}^2, it is probably generated by the detector. The 1/f noise of the PIN photodiode has two components. The noise generated in the junction of the diode, which is proportional to I_{ph}, and the noise of the series resistance, which is proportional to I_{ph}^2. In this current range, the latter seems to be dominant. The noise of the amplifiers (order of magnitude 10^{-28} - 10^{-27} A^2/Hz) is decades lower than the background noise.



(a) (b)

Figure 9 : 1/f Noise in the transmitted light for constant P(L) (a), and for constant P(0) (b); f=1Hz.

5.3 Light-intensity noise as a function of optical fibre length

After modification of the measurement set-up, the measurements on the fibres were redone. They were taken for fibre lengths of 32, 64, 128, 254, and 512 meter respectively. The noise in the transmitted light $S_{P(L)}$, is dependent of fibre length and light power. If the light power at the output P(L) is kept constant, and thus I_{ph}, the noise $S_{P(L)}$ is proportional to fibre length (see eq. 6).

$$S_{P(L)} = P(L)^2 \beta^2 \frac{\varepsilon}{fm} L \tag{13}$$

This is shown in fig.9a. If, however, the light power at the begin of the fibre P(0) is kept constant then $S_{P(L)}$ has a factor proportional to L and a factor exponentialy decreasing with L:

$$S_{P(L)} = P(0)^2 \exp(-2\beta L)\, \beta^2 \frac{\varepsilon}{fm} L \tag{14}$$

This is shown in fig 9b. The curve shows an optimum in $S_{P(L)}$ for fibre lengths in the range 10-500m. The fibre lengths we used are in this range.

The measured values are corrected for background noise. In fig. 10, $f{*}S_{1/f}/I_{ph}^2$ is plotted versus fibre length L. The line in the graph has slope 1. Shorter lengths than 32m were not measured because the noise level was too close to the background noise. Longer lengths than 512m were not available, and even if they were, this would pose considerable problems of coupling enough light into the fibre, and maintain stability at the same time.

The points in fig. 10 show some dispersion with respect to the drawn line of slope 1. For noise measurements, this dispersion is not dramatic. Determination of the 1/f noise level of a spectrum is somewhat arbitrary. The difference in 1/f noise level between the lowest and the highest curve fit that still ' looks good' can amount to a factor of 1.3.

Another possible cause of noise in the transmitted light is noise in the reflection of the fibre end. Fluctuations in refractive index can cause fluctuations in the extinction coefficient, but also in the reflection coefficient. Therefore, reflections at the extremities of a fibre can also be noisy, and will add to the noise due to extinction coefficient fluctuations. Since one cleavage of a fibre is better than another, there will also be a difference in the magnitude of the reflection noise. The reflection noise not being the same for every fibre length, will also contribute to the dispersion.

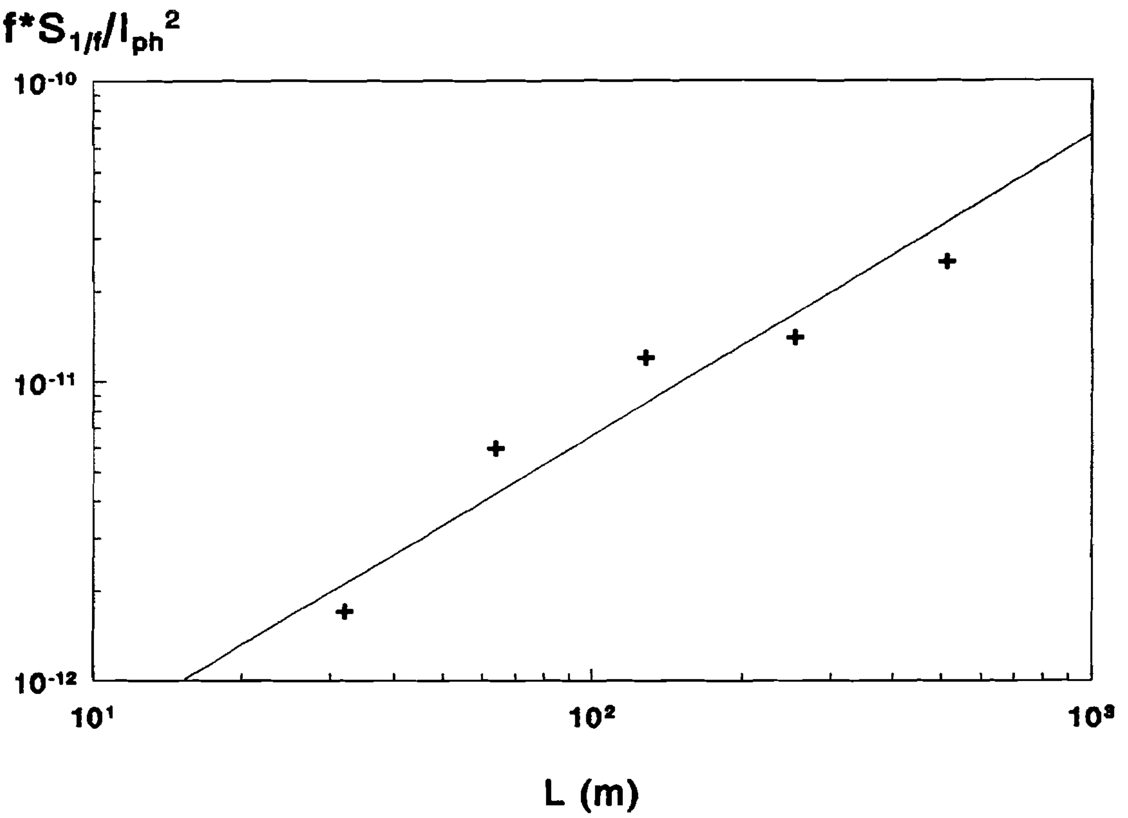


Figure 10 : Normalized 1/f noise $f^*S_{1/f}/I^2_{ph}$ versus fibre length L.

The light is generated by a white light source. The extinction coefficient ß is a function of wavelength; some wavelengths are stronger absorbed than others. For optical fibres, light in the red and near infrared region is transmitted best. The colour of light at the output of a fibre changes with fibre length. For 32m it is yellow, for 512m orange. Since the detector is not equally sensitive for all wavelengths, this could affect the results. If we look at the spectral response of the detector in fig. 4, however, it can be seen that in the wavelength range of interest, from green light (λ =500nm) to near infrared light (λ =900nm), there is no large sensitivity difference.

6 Conclusions

Noise measurements carried out on different optical fibre types, all showed 1/f noise in the light intensity at the output of the fibre. Comparing measurements with a hollow pipe proved that the 1/f noise was originating from the optical fibres.

Light propagating through optical fibres is partly lost. The different loss mechanisms, scattering and absorption, can be combined in one parameter, the extinction coefficient ß. The extinction coefficient fluctuates in time, thus causing fluctuations in the intensity of the transmitted light.

Noise measurements carried out on different fibre lengths show, that the relative 1/f noise in the light intensity is proportional to fibre length. This is in agreement with our model, and shows that the 1/f noise is caused by fluctuations in the extinction coefficient, and is not due to fluctuations in the reflectivity at the ends of the fibre.

Acknowledgments

We would like to thank dr.ir. W.C. van Etten and ing. L.J.P. Niessen of group EC, for supplying the optical fibres.

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

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Indexing terms: optical fibres, 1/f noise

Abstract

The extinction coefficient, used to express losses in optical fibres due to absorption and diffusion, fluctuates in time, with a 1/f spectrum. We 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 on optical inhomogenities and absorption. The extinction is characterized by the extinction coefficient ß. In this parameter, the different loss mechanisms are combined.

This paper shows that the extinction coefficient is not a constant, but fluctuates in time, with a 1/f spectrum. Muscha et al. have done 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.

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 16 dB/km. Fig. 1 shows the set-up used in the experiments. The light source is a halogen lamp. We used a halogen lamp rather than a laser or a 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 analyzer, 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, in order 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 1.4 km, that is cut to different lengths. Measurements are taken with fibre lengths of 32m, 64m, 128m, 254m and 512m.

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. 2a shows a spectrum and the curve fit. The different values of $fS_{1/f}$ are plotted versus photocurrent I_{ph} in fig. 2b.

Since $fS_{1/f}$, the 1/f part of the spectrum at 1 Hz, is proportional to I^2_{ph}, a line of slope 2 can be drawn through the experimental values on a plot of log $fS_{1/f}$ versus I_{ph}^2. On this line, the relative noise $fS_{1/f}/I^2_{ph}$ 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 $fS_{1/f}/I^2_{ph} = 7 \cdot 10^{-13}$, whereas the corrected relative noise is between 10^{-12} and $3 \cdot 10^{-11}$. In fig. 3 relative noise is plotted versus fibre length together with a line of slope 1.

Discussion

Fig. 3 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

$$P(L) = P(0)\exp(-\beta L) \tag{2}$$

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

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

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

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

$$\frac{S_\beta}{\beta^2} \propto \frac{\varepsilon}{f\Omega} \tag{4}$$

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

$$\frac{S_\beta}{\beta^2} = \frac{\varepsilon}{fM} \tag{5}$$

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

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

Hence, the relative 1/f noise in the output light intensity, is proportional to fibre length (fig. 3). This figure shows that the relation between noise and fibre length is

$$\frac{S_I}{I_{ph}^2} = KL\frac{1}{f} \tag{7}$$

with $K = 7*10^{-14}\ m^{-1}$.

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 ß, 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 paper gives a qualitative explanation of this dependence.

Acknowledgment

We thank prof dr. ir. W. van Etten for providing us with the optical fibre.

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Figure captions

Fig.1 Measurement set-up for optical fibre experiments.

Fig.2a Measured noise spectrum with curve fit for 128m fibre. $I_{ph} = 2.60\ \mu A$.

Fig.2b $fS_{1/f}$ versus I_{ph} for the 64m fibre. + =measured values; Δ=corrected for background noise.

Fig.3 Relative 1/f noise $fS_{1/f}/I_{ph}^2$ versus fibre length L.

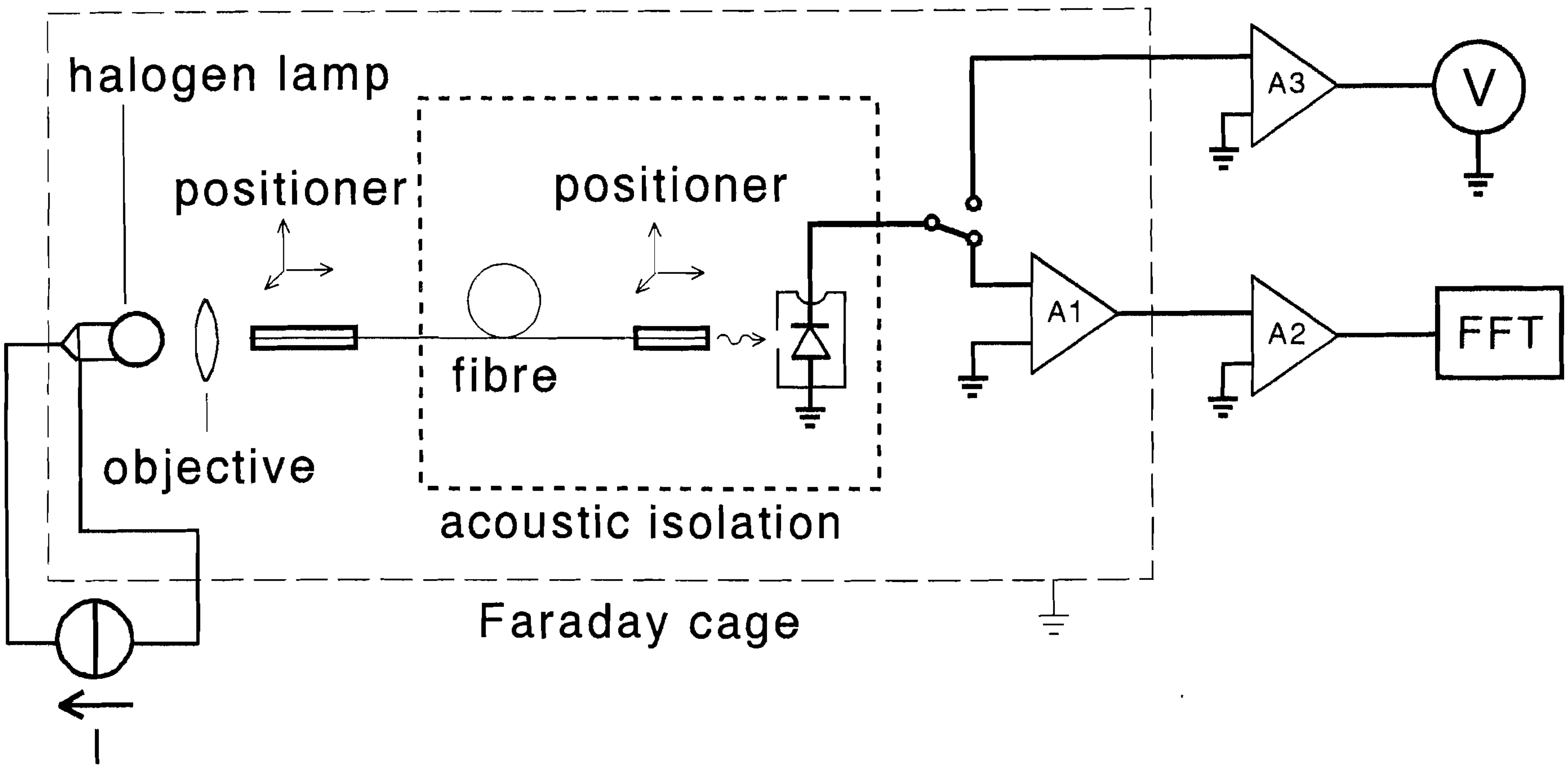
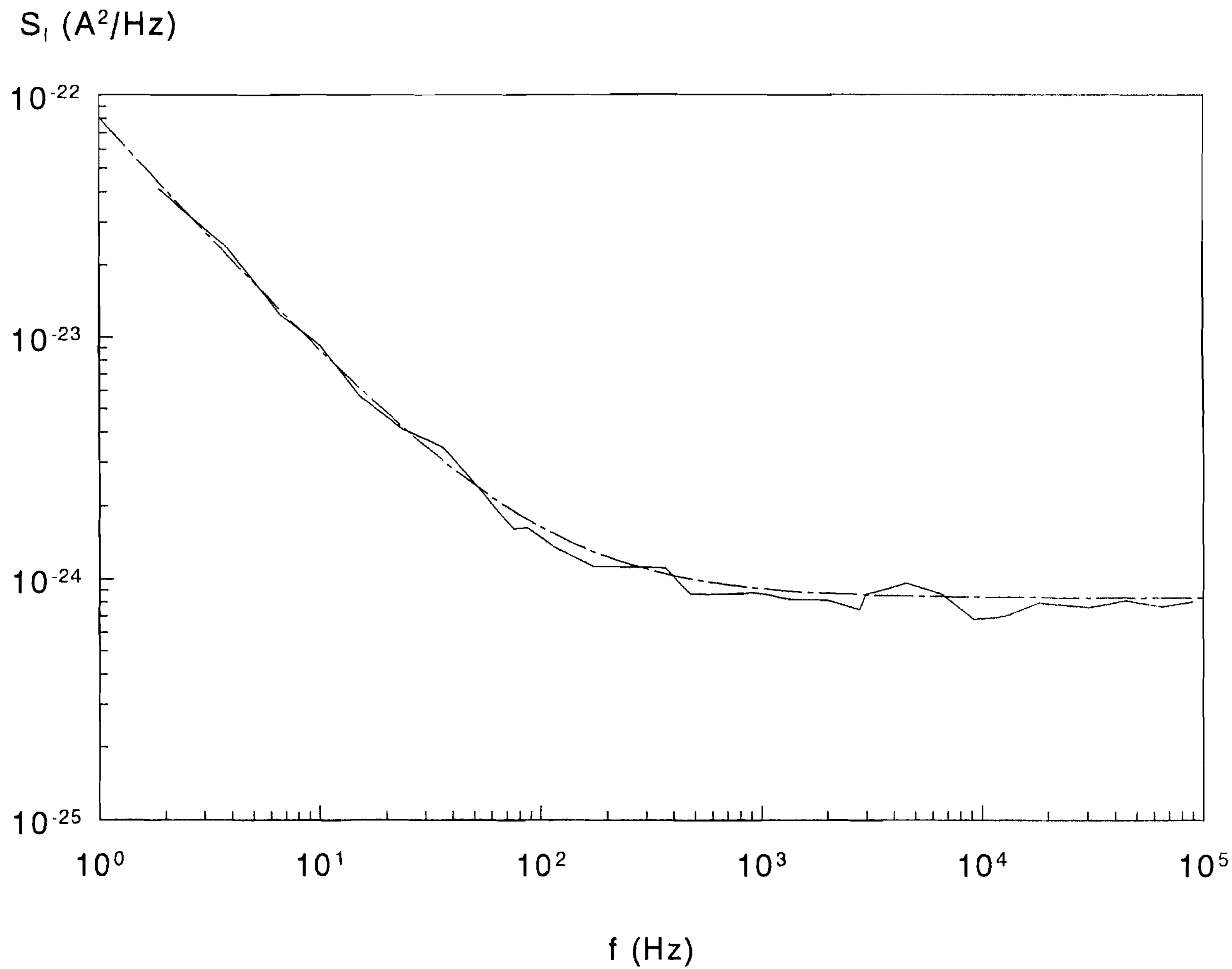

halogen lamp
positioner
positioner
fibre
objective
acoustic isolation
Faraday cage
A3
V
A1
A2
FFT
I

Figure 1


S_I (A²/Hz)
10^-22
10^-23
10^-24
10^-25
10^0
10^1
10^2
10^3
10^4
10^5
f (Hz)

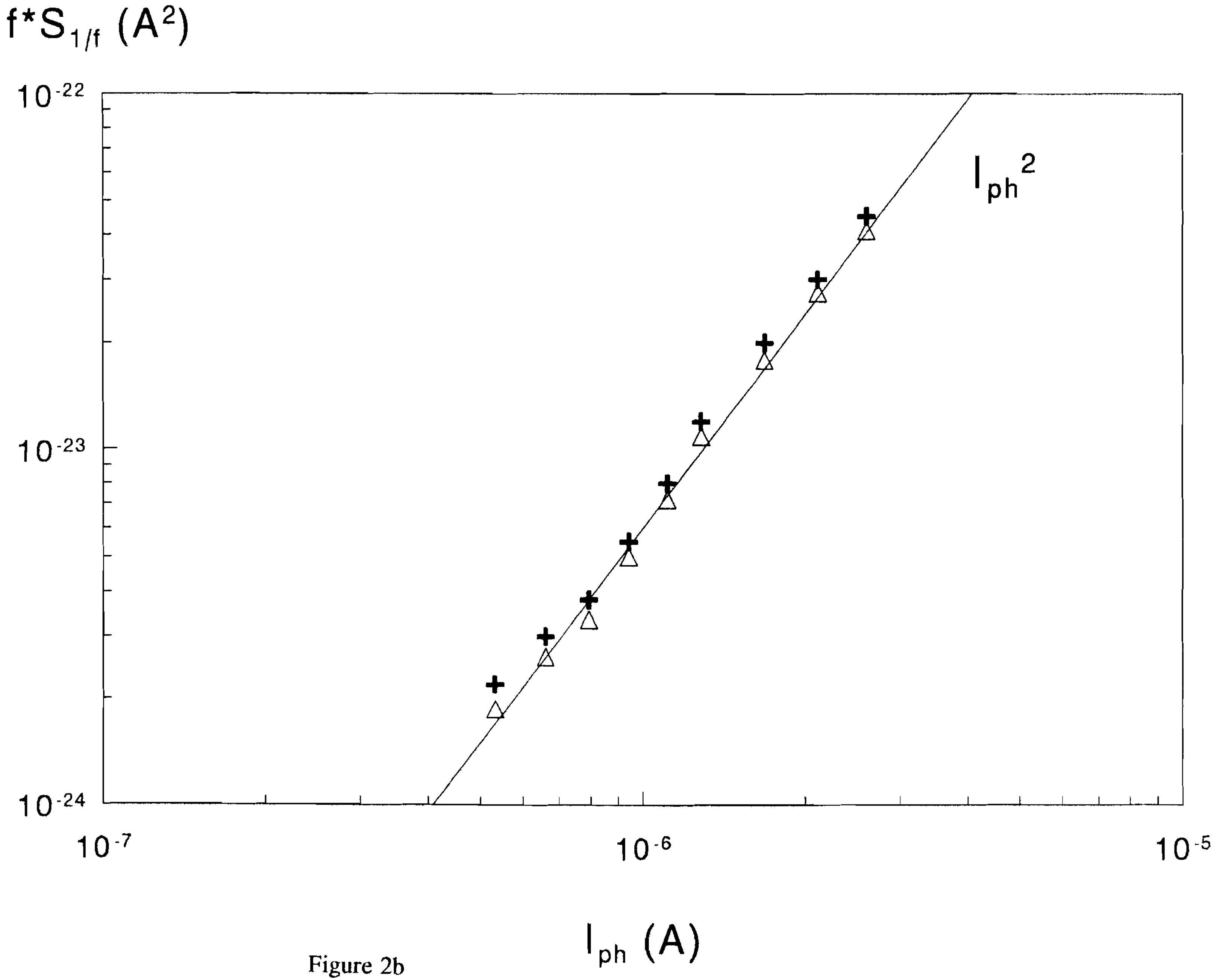


Figure 2b

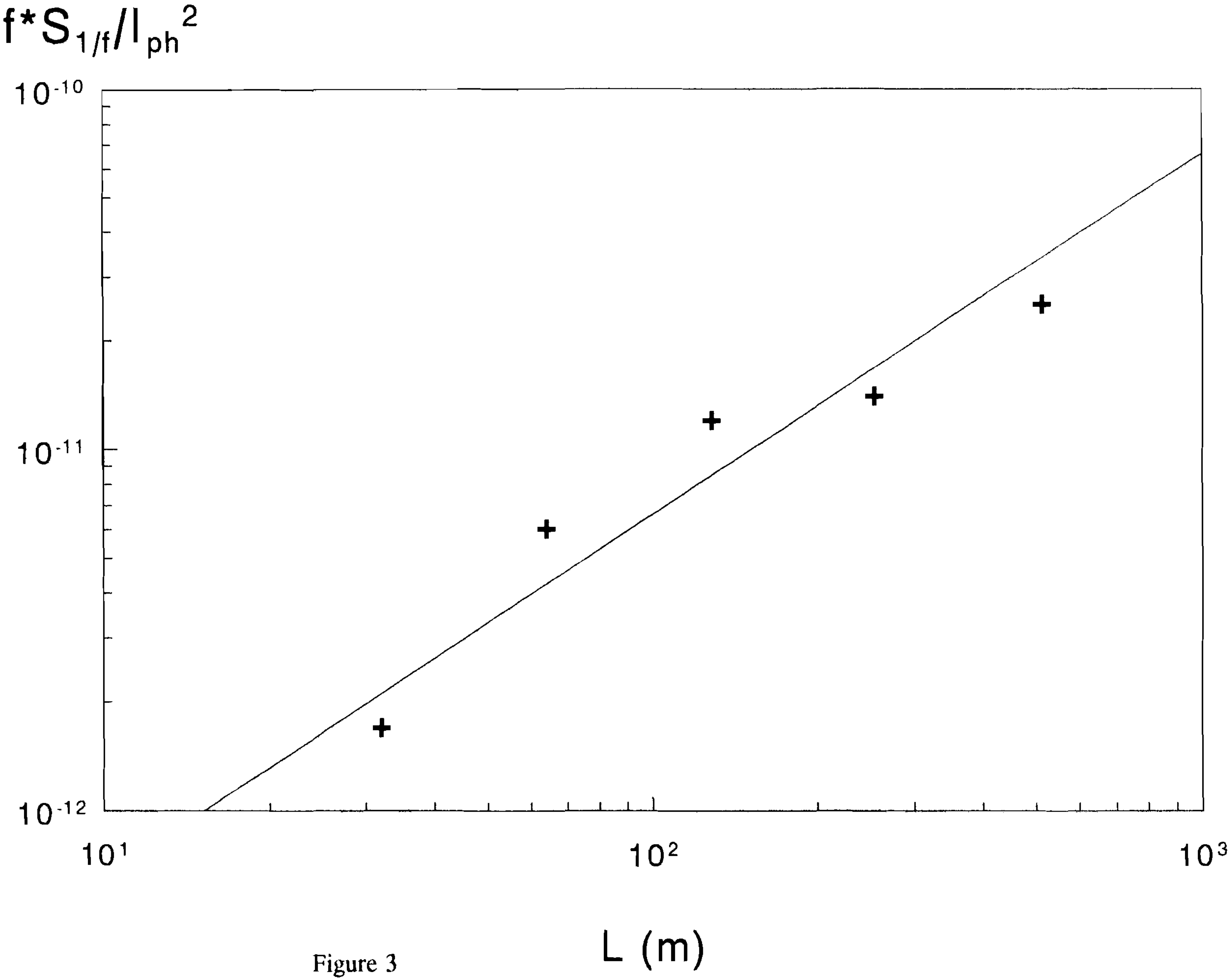


Figure 3