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Estimation of Modal Noise for Arbitrary Connectors, Fibres and Sources

A relation from random sampling theory for estimating the modal noise from monochromatic speckle patterns is extended to polychromatic sources. Comparison with analytical solutions, computer solutions and experimental results shows good agreement. From speckle contrast the ratio of source and fibre bandwidths may be determined.

Abschätzung des Modenrauschens für beliebige Stecker, Fasern und Lichtquellen

Eine aus der Stichprobentheorie bekannte Beziehung zur Abschätzung des Modenrauschens zufolge monochromatischer Granulationsmuster wird für den Fall polychromatischer Lichtquellen erweitert. Der Vergleich mit analytischen Lösungen, Computerrechnungen und experimentellen Ergebnissen zeigt gute Übereinstimmung. Aus dem Kontrast des Granulationsmusters läßt sich das Verhältnis der Bandbreiten der Lichtquelle und der verwendeten Faser ermitteln.

The effect of modal noise is well understood for both open and closed maximum-contrast speckle patterns [1] ($N_{\mathrm{Li}} = 1$, eq. (7)).

Non-maximum-contrast speckle patterns have been treated by a field analysis of a planar waveguide with subsequent application of the results to step-index fibres [2] or by a field analysis in conjunction with computer solutions [3]. Neither approach allows a quick estimate of the amount of modal noise to be expected for a given connector, light source, fibre type and fibre length in a practical situation. Such an estimate is given below.

From sampling theory [1], [4], [5] the relative fluctuation of the output power P_{o} of the connector for a closed input speckle pattern and uniform modal power distribution is given by

$$\frac{\overline{\delta P_{\mathrm{o}}^2}}{\bar{P}_{\mathrm{o}}^2} = C^2 = \frac{N_{\mathrm{i}} - N_{\mathrm{o}}}{N_{\mathrm{o}}(N_{\mathrm{i}} - 1)} \,. \tag{1}$$

C is named speckle contrast. N_{i}, N_{o} denote the numbers of countable speckles in the input and output fibres, respectively. The power coupling efficiency of the connector (which may be measured) is given by the quotient of the degrees of freedom

$$\eta = \bar{P}_{\mathrm{o}}/P_{\mathrm{i}} = N_{\mathrm{o}}/N_{\mathrm{i}} \,. \tag{2}$$

The number N of countable speckles is the number N_{T} of speckles in a monochromatic, fully polarised pattern (number of "transverse" speckles) multiplied by the number N_{L} of independent patterns differing in wavelength (number of "longitudinal" speckles) times a factor of two for the two possible independent polarisations:

$$N_{\mathrm{i}} = 2 N_{\mathrm{Ti}} N_{\mathrm{Li}} \,, \quad N_{\mathrm{o}} = 2 N_{\mathrm{To}} N_{\mathrm{Lo}} \,. \tag{3}$$

The number of guided modes M_{gi} in the input fibre equals the number of speckles in two polarisations of a monochromatic pattern

$$M_{\mathrm{gi}} = 2 N_{\mathrm{Ti}} \,. \tag{4}$$

In most practical cases $N_{\mathrm{Li}} = N_{\mathrm{Lo}}$, since there is no spectral filtering at the connector. The factor 2 must be omitted in N_{o} if there is a polariser in the connector.

The number N_{Li} may be found from the following consideration: The particular form of the speckle pattern at the endface of the input fibre is determined by the phases of the cross-terms between the modal fields, which are of the form

$$(\beta_n - \beta_m) L = [\beta_n(\omega_0) - \beta_m(\omega_0)] L + (t_{\mathrm{g}n} - t_{\mathrm{g}m})(\omega - \omega_0) + \cdots \tag{5}$$

β_n, β_m are the propagation constants, $t_{\mathrm{g}n}$, $t_{\mathrm{g}m}$ the group delays of the modes n, m along the fibre of length L.

If for a change in frequency by an amount $f - f_0 = \Delta f_{\mathrm{c}}$ the phases of the cross-terms have dispersed over a range 2π, the corresponding speckle patterns will be independent. From eq. (5) a correlation-bandwidth Δf_{c} is defined through

$$(t_{\mathrm{g}n} - t_{\mathrm{g}m})_{\max} \Delta f_{\mathrm{c}} = 1 \,. \tag{6}$$

$(t_{gn} - t_{gm})_{max}$ may be taken either from theory or from measurements of the width of the impulse response of the fibre. The theoretical correlation bandwidth from eq. (6) for a step index fibre is $\Delta f_c = c/(L n_g \Delta)$, which is in excellent agreement with experimental results [2]. Eq. (33) in [2] yields for a planar waveguide $\Delta f_c = 0.75 c/(L n_g \Delta)$.

If a light source with a continuous spectrum radiates within a bandwidth Δf_s, and if the correlation bandwidth of the fibre of length L is given by Δf_c, then

$$\begin{aligned} N_{Li} &= \Delta f_s/\Delta f_c, & \Delta f_s &\geqq \Delta f_c, \\ N_{Li} &= 1 \text{ (max. contrast)}, & \Delta f_s &\leqq \Delta f_c. \end{aligned} \tag{7}$$

For sources with a line spectrum Δf_s must be properly interpreted.

The relative power fluctuations due to modal noise, eq. (1) for given Δf_s, η, $(t_{gn} - t_{gm})_{max}$, M_{gi}, are computed as follows: Δf_c, N_{Li}, N_i, N_o are found from eqs. (6), (7), (4)+(3), (2), respectively; N_i, N_o are then inserted into eq. (1); a detailed discussion is given elsewhere [6].

For $N_{To} = 1$ and multimode fibres ($N_{Ti} \gg 1$) we have from eqs. (1), (7)

$$\Delta f_s/\Delta f_c = 1/(2C^2) = N_{Li}. \tag{8}$$

From a measurement of the speckle contrast with $N_{To} = 1$ and known Δf_c the source bandwidth or, alternatively, for a certain Δf_s the fibre bandwidth may be estimated from eq. (8).

Fig. 5 of [3] gives computer solutions for the speckle contrast of a connector with $\eta = 0.8$ for two different α-profiles ($\alpha = 2.05$ and 2.3) and two different V-parameters ($V = 21$ and 31) as a function of τ_{rms}/τ_c, where τ_{rms}, τ_c denote the root-mean-square pulse broadening of the fibre and the coherence time of a source with Lorentzian line shape. Assuming for simplicity the relations $\Delta f_s \tau_c = 1$, $\Delta f_c \tau_{rms} = 1$ one obtains $\tau_{rms}/\tau_c = \Delta f_s/\Delta f_c = N_{Li}$. The number of guided modes in α-profiles is known to be $M_{gi} = 0.5\, V^2 \alpha/(2+\alpha)$. For these parameters one obtains from eq. (1) values for the speckle contrast which are in reasonable agreement (10—20% larger) with the computer results given in [3].

To illustrate the application of eq. (1) the following experiment has been designed: The light emitted from a temperature stabilised V-groove laser (AEG-Telefunken) with 5 mW power output (11 lines in a HPBW of 2.19 nm, about 0.5 mW per line) was passed through a Jobin-Yvon monochromator HRP (focal length 0.6 m, resolution 0.2 Å). $1 \leqq M \leqq 7$ axial modes (mode spacing approximately $\Delta f_{MS} = 100$ GHz) with relative weights 1, 0.97, 0.93, 0.89, 0.86, 0.75, 0.81, grouped symmetrically to the centre mode ($\lambda = 819$ nm, long-term mode width $\Delta f_M \approx 7$ GHz) were selected. Due to losses only 8 μW per line were available at the fibre input. The waveguide modes were mixed by microbendings, the cladding modes removed and the leaky waves reduced. Because of the low power level a direct contrast measurement [5] of the unpolarised speckles with $N_{To} = 1$ became difficult. Therefore the radiated far-field was imaged and 15 times amplified by an infrared image converter, the screen of which was recorded on an AGFA-PAN 25 negative film. The transparency contrast of the film equals the speckle contrast C, if the amplification of the image converter and the film exposure are properly chosen and if unpolarised speckle patterns are recorded (the probability [7] that an intensity is nonlinearly recorded may be kept less than 10%).

It is further assumed that the contrast at a fixed point of the fibre endface ($N_{To} = 1$) in a changing speckle pattern [5] equals the contrast seen by a moving point in a frozen speckle pattern. The contrast was measured by scanning the rotating film (2.8 rps) along a spiral centered on the far-field axis with a HeNe laser beam ensuring $N_{To} = 1$. Averaging over 10 s yielded the mean transmitted power and the rms-value. During the measurement time of 900 s 90 different transparency contrasts were calculated, averaged and the standard deviation determined. This average was accepted as contrast C for one specific pattern.

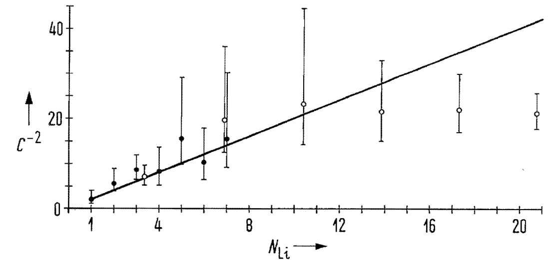

Fig. 1. Reciprocal squared speckle contrast in dependence of the number N_{Li} of independent patterns; —— $C^{-2} = 2N_{Li}$, eq. (8); measured points: ○ fibre A, ● fibre B.

Fig. 1 shows the measured contrasts for unpolarised speckle patterns as a function of the number N_{Li} of independent patterns for two fibre types; the straight line in Fig. 1 is eq. (8), the circles represent the measurements.

Fibre A is a 10 m-long step-index waveguide (Siemens No. 1436/173) with $\Delta f_{cA} = 4$ GHz calculated from the numerical aperture. For one laser mode $M = 1$ the speckle contrast is $C_{AM} = 0.38$, hence from eq. (8) we have $N_{Li} = 3.46$. For M laser modes $N_{Li} = 3.46\, M$. The error bars indicate the range for 68% of the averaged contrasts. For $M > 4$ ($N_{Li} > 13.84$) the contrast is larger than predicted by eq. (8) and shows a tendency to saturate. This is due to the experimental setup, in which for $M > 4$ the laser modes are imaged near the cladding, thus exciting higher fibre modes which have higher losses. The different weights of the axial modes raise [7] for $M = 7$ the expected contrast by less than 0.4% and therefore are of no importance.

Fibre B is a 2.3 m-long graded index guide (SEL B 198) for which a dispersion of 1.6 ns had been measured for 2 km fibre length. Data concerning the coupling length of the fibre were not available. The correlation bandwidth Δf_{cB} of the used 2.3 m-long fibre, however, has to be somewhere between the possible extremes obtained from square root scaling (full mode coupling) or linear scaling (no mode coupling), yielding the inequalities 18 GHz $< \Delta f_{cB} <$ 540 GHz. Therefore Δf_{cB} is certainly larger than the bandwidth $\Delta f_M \approx 7$ GHz of a single laser mode, and possibly larger than the spacing $\Delta f_{MS} = 100$ GHz of adjacent laser modes. From the measurements a linear increase of $1/(2C^2)$ follows for illumination of the fibre with $M = 1, 2, 3$ laser modes. From this it may be concluded that different laser modes give origin to independent speckle patterns, and it is reasonable to put $N_{Li} = M$ for these measurements as has been done in Fig. 1. The actual correlation bandwidth of the fibre length used in the measurements must be in the vicinity or smaller than the laser mode spacing $\Delta f_{MS} = 100$ GHz.

Using eq. (8) and $C_{AM} = 0.38$ for fibre A the long-term axial mode bandwidth of the laser may be estimated to be $\Delta f_S = \Delta f_M \approx 14$ GHz, in reasonable order-of-magnitude consistence with direct spectrography near the instrumental resolution limit.

Conclusion: Eq. (1) gives a good, simple estimate of modal noise for arbitrary connectors, fibres and sources. Eq. (8) offers a new uncomplicated method to determine the spectral width of lasers or, if the laser spectrum is known, to measure the fibre bandwidth.

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