Polarization effects in a single mode optical transmission link

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Polarization dispersion is an effect which may cause data rate penalty in optical links. This is caused by the combined effect of fibre birefringence and polarization couplings due to environmental perturbations. Polarization dispersion is therefore a stochastic quantity and results in a fluctuating pulse broadening, making only an expectation value to be forecast. In practical systems this dispersion can be neither avoided nor cancelled.
The different methods for polarization dispersion measurements reported to-date are described. Details of the experimental set-up and results are shown for the interferometric loop technique, which easily enables the polarization dispersion expectation value to be measured using a particularly simple e set-up.

Effets de la polarisation dans une ligne de transmission optique monomode

La dispersion de polarisation est un effet qui peut limiter le débit d'information dans une ligne de transmission optique. Elle est due à l'éffet combiné de la biréfringence de la fibre et de couplages de polarisation causés par des perturbations externes. La dispersion de polarisation est de ce fait une grandeur aléatoire donnant lieu à des fluctuations dans l'élargissement final de l'impulsion. Ainsi, seule une valeur moyenne pourra être déterminée. Cette dispersion ne peut être, en pratique, pas évitée et encore moins annulée.
Les différentes méthodes de mesure de la dispersion de polarisation, publiées à ce jour, sont décrites. La technique de la boucle interférométrique est en particulier exposée, avec des détails expérimentaux et des résultats. Cette dernière méthode permet de mesurer la valeur moyenne de la dispersion de polarisation à l'aide d'un dispositif expérimental particulièrement simple.

Effekte der Polarisation in einem monomoden faseroptischen Übertragungssystem

Die Dispersion der Polarisation ist eine Erscheinung, die eine Beschränkung der Datenraten in einem optischen Übertragungssystem bewirken kann. Diese ist durch den kombinierten Effekt der Faserdoppelbrechung und der Polarisationskopplung verursacht, der durch die Umgebungsstörungen entsteht. Deshalb ist die Dispersion der Polarisation eine stochastische Grösse, die die Fluktuationen in der Pulsausbreitung bewirkt. Als Folge kann nur ihr Erwartungswert bestimmt werden. In den reellen Systemen kann die Dispersion weder vermieden noch aufgehoben werden.
Es wurden verschiedene Methoden für Messungen der Dispersion der Polarisation publiziert. In diesem Beitrag werden die Einzelheiten der Messapparatur und die Messergebnisse, die mittels eines interferometrischen Ringes gewonnen wurden, besonders gezeigt. Diese einfache Methode ermöglicht leicht die Messung des Erwartungswerts von Dispersion der Polarisation.

Introduction / Introduction

Chromatic dispersion is a well-known effect causing pulse broadening and data rate penalty. This effect can be made negligible by using a single mode laser source or by properly designing the optical fibre, so that its zero dispersion wavelength corresponds to that of the light source. In this way the single mode fibre is expected to add no actual bandwidth limitations to the system.
Nevertheless anisotropies within a single-mode optical fibre may induce polarization-dependent properties for the light propagation. This globally results, in a pulse broadening, so that this effect is now commonly called polarization dispersion. It strongly depends on how the fibre was designed, processed and cabled, so that it is hardly avoidable and cannot be cancelled unless using special fibres or a complicated active light polarization control.
The understanding of polarization behaviour in a randomly anisotropic medium such as an ordinary single-mode fibre has given rise to theoretical works [1-6], that resulted in a model conveniently describing the observed effects, using the so-called *principal states of polarization*.
On the other hand the need of polarization dispersion actual evaluation gives rise to an experimental challenge. Several techniques have been proposed to-date and Swiss research groups occupy a top position in this field.

Phenomenological background

In any optically anisotropic medium the light velocity depends on the orientation of the light polarization. This causes the state of polarization to be transformed when light propagates through the medium. The polarization direction remains but unchanged when it corresponds to any of two special orthogonal directions called the *eigenstates* of polarization. For each of these two directions a different refractive index – or light velocity – is defined. This medium property is named *birefringence* or double-refraction.
Any polarization direction can then be projected over these directions, resulting in two lightwaves propagating at different velocities. When optical pulses such as in a transmission link are concerned these different velocities give progressively rise to a pulse splitting, as shown in fig. 1. This results in an overall pulse broadening and even in a distinct pulses overlapping, reducing the data rate capability. Birefringence may therefore decrease the bandwidth this way.

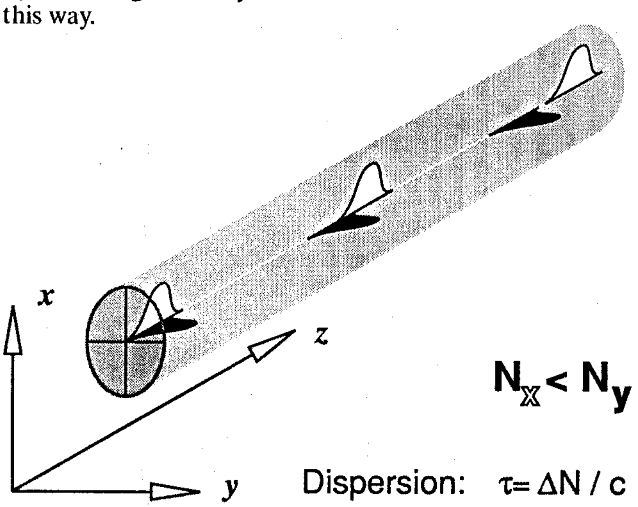

Fig. 1: Light pulses propagating along the two orthogonal birefringence axes travel at different velocities, resulting in a pulse broadening or ever splitting.

In an actual standard single mode fibre the cylindrical geometry makes no transversal directions particular and no birefringence should therefore be observed. Nevertheless a perfect cylindrical geometry is never actually obtained and internal strains are always frozen within the fibre during the drawing process, so that such a fibre always shows a slight birefringence and thus gives rise to pulse broadening.
This could be prevented by launching the light from the source with a polarization corresponding to an eigenstate of polarization. But an actual installed fibre experiences accidents, as shown in fig. 2, making the birefringence magnitude and the eigenstates direction to locally change. Furthermore these local changes are slowly time-dependent owing to fibre mechanical relaxation and temperature changes, so that the eigenstates of polarization – and thus the light output polarization direction – is unpredictable and randomly time-varying.

Fig. 2: Installed optical fibres experience environmental perturbations making the polarization properties to locally change.

This behaviour can be conveniently described by a polarization coupling complex coefficient γ that varies along the fibre, as shown in fig. 3. Using this model local variations of birefringence are set equivalent to coupling between orthogonal polarizations, that is, part of the light intensity in each intrinsic eigenstates of polarization are mutually exchanged. The amount of transferred light is given by the γ coefficient.

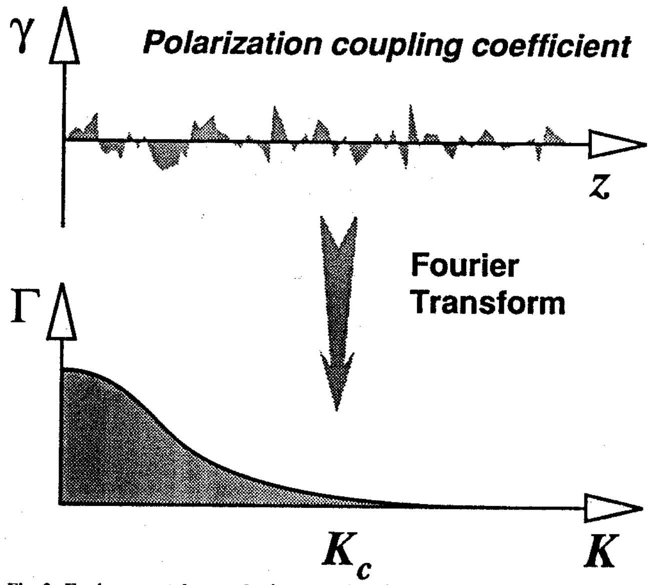

Fig. 3: Environmental perturbations are described by a polarisation coupling coefficient γ depending on the position z along the fibre. The random nature of the perburbations results in a Gaussian distribution in the spatial frequency domain.

The Fourier transform of the γ coefficient yields the amount of polarization coupling as a function of spatial frequency. The random nature of these couplings makes the coefficient to be described by a Gaussian law in the frequency domain. A spatial frequency limit K_c can be defined over which polarization couplings are unlikely to occur. This limit strongly depends on the cabling process and the installation, but it has been actually observed to always be within a definite range of value for standard cables.

Strong polarization coupling is expected only if the perturbation is resonant with the unperturbed levels, that is, if the polarization coupling coefficient has a significative amplitude at a spatial frequency equal to the intrinsic birefringence beat frequency. This condition is given by the following relationship $k \Delta n < K_C$ where $k = \omega c$ is the light wavenumber. This condition is always fullfilled in ordinary single mode fibre, so that strong polarization couplings always occur in such fibres.

When a pure well-defined polarization state has to be maintained along the fibre, polarization couplings must in no way occur. This can be achieved using fibres with high intrinsic birefringence, as shown in fig. 4, so that a perturbation spatial frequency component is unlikely to be resonant with the birefringence beat frequency. Such fibres require special designs and manufacturing processes owing to the high birefringence required and are now commonly commercially available. They can maintain polarization over several tens of kilometer.

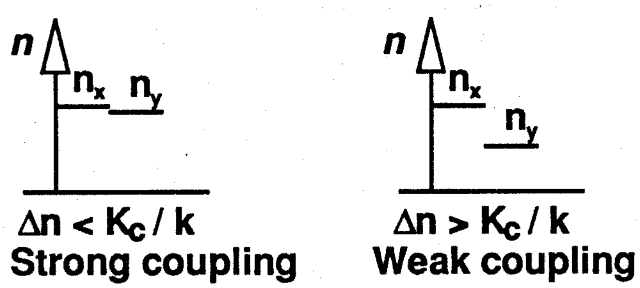

Fig. 4: When the spatial frequency of the perturbation is resonant with the birefringence beat frequency, polarization couplings can efficiently occur. When the birefringence is high, perturbations with such a high spatial frequency are unlikely, making the polarization direction to be unperturbed and maintained along the fibre.

In a standard fibre light is often coupled from one polarization eigenstates to the other, so that part of the light randomly moves from the fast mode to the slow, part of it returns to the fast, and so on. The equations describing such a behaviour are formally similar to diffusion equations, such as those describing random walks of colliding particles, as shown in fig. 5. In this case the pulse broadening has to be identified to the total distance from the starting point. This formal identification allows two important consequences to be stated:

- Pulse broadening due to polarization dispersion randomly varies. It is a *stochastic* quantity and only its expectation value can be forecast. Its probability density function is a Maxwell distribution, just like the total distance in any diffusion process.
- The expectation value of pulse broadening always increases with distance, so that polarization dispersion can be in no way cancelled out. As in any diffusion process the expectation value grows as the square root of the distance.

For such fibres latest theories [1, 2] show that the best set of orthogonal polarization states suitable to describe pulse broadening effects is *not* the eigenstates of polarization, but the so-called *principal* states of polarization. These principal states have the property to be first-oder invariant to light frequency changes, that is, when light from the source is launched along one of these states the output light polarization at the far end remains unchanged when the source wavelengh is slightly shifted. Ik can be demonstrated that polarization dispersion – the actual pulse broadening – is equal to the group delay between the principal states. Furthermore polarization dispersion is straightforwardly related to the rate of change of the output polarization when source frequency is varied, provided that light is launched along a polarization direction different to a principal state.

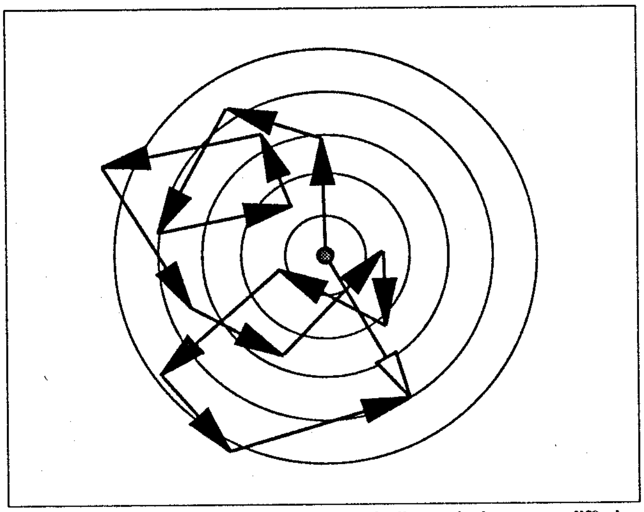

Fig. 5: Polarization dispersion is mathematically equivalent to a diffusion process. Each section between polarization couplings makes the pulse width to randomly increase or decrease, so that the total pulse broadening (white arrow) is quite different than expected by the single effect of birefringence.

Measurement techniques

The first reported measurement method [5, 6] uses the above described property that polalization dispersion is equal to the rotation rate of the output polarization when the source wavelength is changed. The light of two laser sources having close emission wavelengths is sequentially launched into the test fibre and the two angles necessary to fully determine the output polarization are measured using a polarimeter. The rate of change of the output polarization gives the polarization dispersion. Actually two laser sources are not sufficient to perform accurate and unambiguous measurements, so that a tunable laser source is preferably used. The stochastic nature of polarization dispersion makes the measurements to be repeated many times by changing the environmental conditions, so that a set of statistically independent measurements can be collected and an expectation value can be determined.

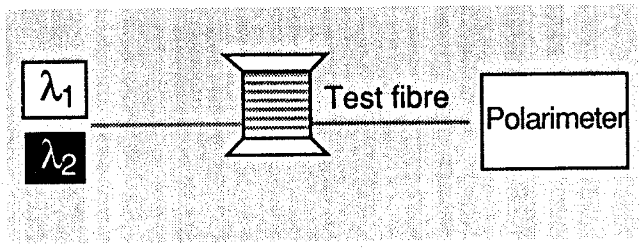

Fig. 6: Experimental scheme of the method measuring the rotation of polarization states to determine polarization dispersion.

Another technique has been developped at the University of Geneva [7] and relies upon interferometric delay measurements. A white light interferometry method has been used, for which a broad spectrum – or low-coherence – source is needed. In this case interferences are observed using a Michelson interferometer only within a narrow detuning distance, so that the presence of interferences can be used as time marker with an accuracy in the femtosecond (10^{-15} s) range. When light has propagated throughout the fibre to be measured, the combined effect of birefringence and polarization couplings makes the interferometric analysis at the output to give numerous interference markers representing all the possibilities for the light to propagate and thus the actual distribution of polarization dispersion. This analysis can be successfully achieved, provided that a polarization maintaining interferometer is used. This method has the great advantage to directly yield the statistical distribution of polarization dispersion. The actual measured distribution matches fairly well a Gaussian law, as predicted by the model.

A different method has been developped at the Metrology lab at EPFL [8], which also yields the distribution of polarization dispersion. The experimental set-up is particularly simple, as shown in Fig. 7. It only uses a spectrally tunable light source, such as a halogen lamp followed by a monochromator, a sensitive detection and a single mode fibre coupler. The monochromator, the detector and the lock-in amplifier can be replaced by an optical spectrum analyser. The measure principle relies upon an interferometric loop technique or Sagnac interferometer.

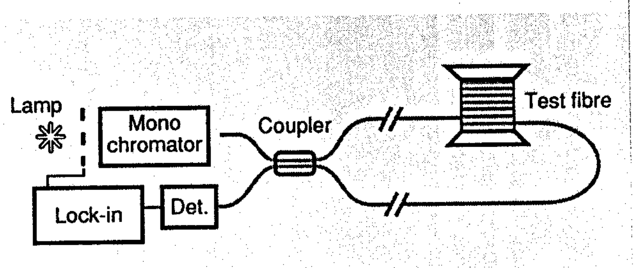

Fig. 7: Experimental set-up of the interferometric loop method.

In this configuration light from the source splits in the coupler and propagates through the fibre in two counterpropagating directions. These counterpropagating waves then superpose when merging in the coupler again and thus interfere. This configuration is very stable because the lightwaves propagate through the same medium, making the effect of thelmal expansion and mechanical perturbations to be automatically equalized.

The principle of measurement using this configuration is shown in Fig. 8. Let assume the fibre to be birefringent and the directions of the eigenstates of polarization to be indicated by the black and white arrows. When the fibre is neither twisted nor topologically rotated, the directions of the eigenstates are parallel at both fibre ends, so that light propagates in the same polarization eigenstate in both directions, that is, at the same velocity using the same optical path and are in any case in-phase at the output. The response of the interferometer is invariant and gives no information in this situation.

Now when the fibre experiences a 90°-twist or an equivalent topological rotation, as shown in the right side of Fig. 8, the eigenstates directions at each end are interchanged, so that light propagates in a different eigenstate for each counterpropagating direction. Thus these lightwaves tra-

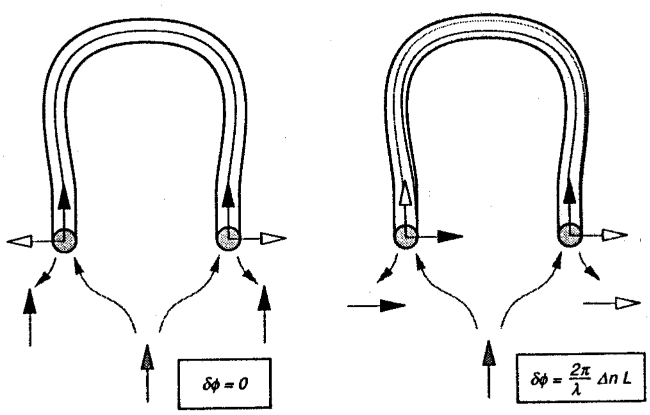

Fig. 8: Effect of birefringence in a fibre interferometric loop and observed phase difference between counterpropagating lightwaves. Left: non-twisted fibre. Right: 90° twisted fibre.

vel along the fibre with different velocities and are not necessarily in-phase at the output. Their phase difference $\delta\phi$ is given by

$$\delta\phi = \frac{2\pi}{\lambda} \Delta n \; L$$

where λ is the light wavelength, L the fibre length and Δn the refractive index difference between the eigenstates, which corresponds to the propagation velocity difference or birefringence. This phase difference can actually only be changed by modifying the light wavelength because Δn and L are fixed quantities. When the wavelength λ is scanned the superposed lightwaves at the output pass from an in-phase to an out-of-phase situation, giving rise to a succession of constructive and destructive interferences resulting in a periodic variation of the interferometer output intensity. The higher the birefringence Δn, the faster the periodic variations are, so that the period measurement actually yields an evaluation of birefringence and hence polanzation dispersion.

This is what is actually observed when measuring a highly birefringent fibre, as shown in Fig. 9, for which no polarization coupling occurs. The fibre has been twisted until maximum interference contrast is observed. The period of the intensity spectral variations is obtained by performing a Fourier transform, so that the polarization dispersion corresponds to the peak position of the transformed distribution, as shown in Fig. 10.

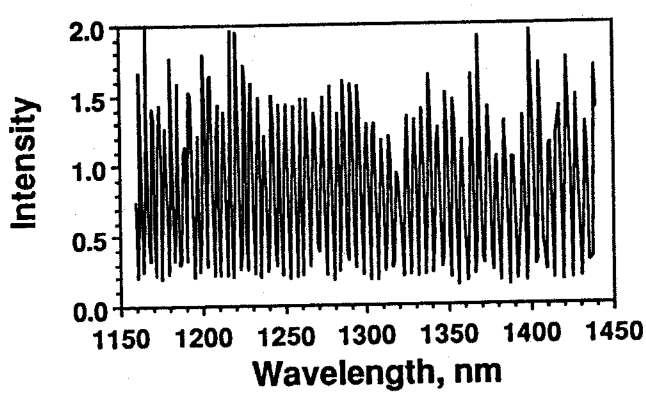

Fig. 9 Measurement of the interferometric loop output intensity as a function of wavelength. The loop is a 0.5 m highly birefringent fibre.

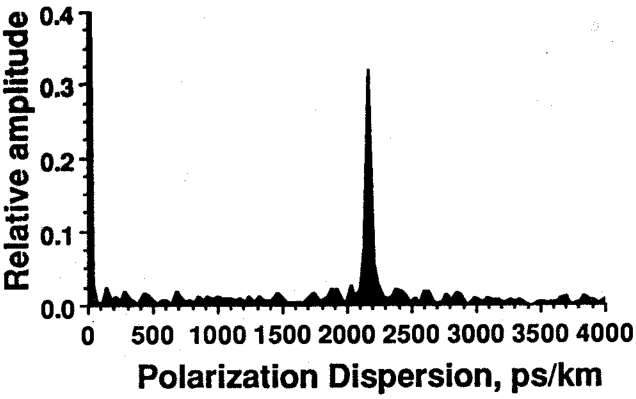

Fig. 10 Fourier transform of fig. 9 measurements. One frequency is mostly present and appears like a peak in the distribution, corresponding to the polarization dispersion value.

The observed intensity variations are quite different when the birefringence is low and accidentally induced such as within a standard fibre, as shown in Fig. 11. In this case numerous polarization couplings occur. When the wavelength is scanned the birefringence makes the light polarization direction to change at the polarization coupling locations, so that the amount of coupled light between polarizations at these locations also depends on wavelength. The delay between polarization is therefore wavelengthdependent, making the period of intensity changes to be irregular over the spectrum, as shown in Fig. 11. The Fourier transform of such a measurement is not just one peak, but a distribution of many peaks, as shown in Fig. 12. The wavelength scan is expected to make the fibre experience a great number of polarization coupling situations, so that it may be equivalent to an ensemble average. With this assumption the distribution obtained by performing the Fourier transform is a measure of the actual polarization dispersion statistical distribution.

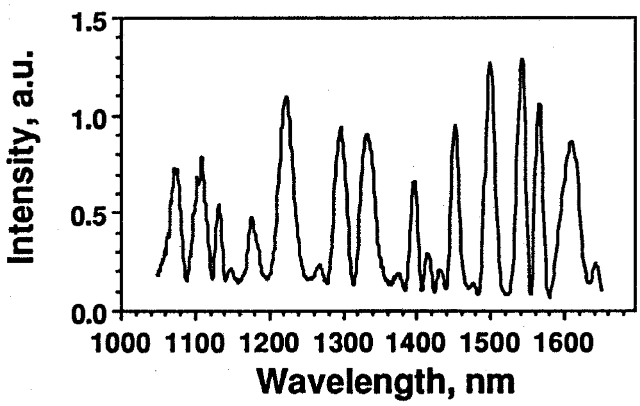

Fig. 11 Measurement of the interferometric loop output intensity as a function of wavelength. The loop is a 3600 m standard single mode fibre.

The obtained distributions, as that shown in Fig. 12, fit very well a Gaussian law and results are reproducible and consistent with measurements performed using other methods. This method has the further advantage to be very easy to implement, because the optical circuit requires only one component - the single-mode coupler - and no polarization-dependent devices such as polarizers and phase retardation plates. Most of the set-up elements are available in any optics lab and the implementation of this technique could be already affordable by many of them. Many installed cables have been successfully measured in Switzerland using this method.

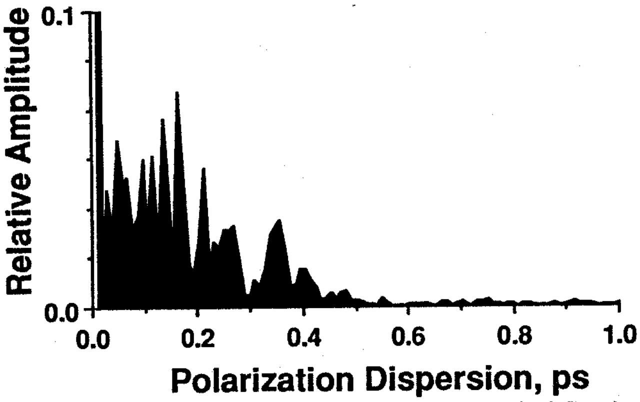

Fig. 12 Fourier transform of fig. 11 measurements. The obtained Gaussian distribution corresponds to the statistical distribution of polarization dispersion.

Acknowledgements

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