3 SANO, K., KUDOU, T., and OZEKI, T.: 'Simultaneous measurement of group delay time dispersion and polarization mode dispersion'. Proc. ECOC'96, Oslo, Norway, 1996, TuP.09
4 FLAVIN, D.A., MCBRIDE, R., and JONES, J.D.C.: 'Demodulation of polarimetric optical fibre sensors by dispersive Fourier transform spectroscopy', *Opt. Commun.*, 1998, **V.156**, (4-6), pp. 367–373
5 HEFFNER, B.L.: 'Automated measurement of polarization mode dispersion using Jones matrix eigenanalysis', *IEEE Photonics Technol. Lett.*, 1992, **4**, pp. 1066–1069
6 DERICKSON, D. (Ed.): 'Fibre optic test and measurement' (Prentice Hall, 1998)

Electro-optic dynamics in thermally poled Ge core doped silica fibre

A.C. Busacca and D. Faccio

The electro-optic (EO) dynamics of a twin hole germania core doped fibre when an applied electric field at elevated temperature modifies the symmetry of glass is reported. An EO peak was recorded after 10 min poling. The results were interpreted with a two-space charge model.

Introduction: Silica is widely used in optoelectronics. Since it is an amorphous material with a centro-symmetric structure it does not exhibit any second-order nonlinearity. Several techniques have been identified to induce a permanent second-order susceptibility in silica and hence a linear electro-optic (EO) coefficient. Among these techniques, thermal poling is considered to be the most reliable. This process relies on the creation of an electrostatic electric field frozen in the glass, that breaks the symmetry of the glass itself, and when coupled with the third-order susceptibility gives an effective second-order nonlinearity. If implemented in silica fibre, thermal poling is a promising technology in the design of WDM router and de-router devices based on wavelength conversion, direct modulators in high bit rate Telecom systems and active Fabry-Perot cavity sensors using Bragg grating reflectors.

In the work reported in this Letter, we thermally poled a specially designed germania core doped twin hole fibre. We give quantitative results on the fibre nonlinearity evolution against the poling time and we interpreted them with consideration of a two-charge migration model. The aim is to compare the dynamics of the nonlinear coefficient in poled fibres with the one found in bulk glasses [1].

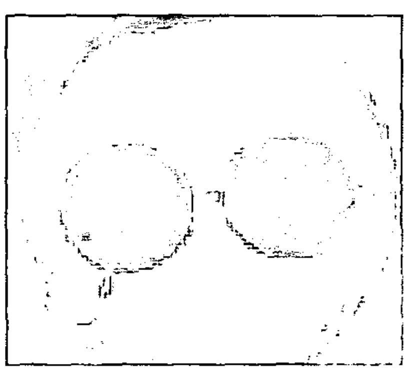

Fig. 1 *Twin hole fibre used for electro-optic coefficient measurements. Electrode spacing in this NA 0.32 fibre is 10 μm*

Experiment: A series of twin hole fibres (Fig. 1) with high germania core doping ($NA = 0.32$) have been poled, varying the time. They have been designed to keep the anode 10 μm apart from the cathode and to have a short distance between the anode and the core (2 μm). In this particular geometry, since the distance anode-core has been designed to be small, the barrier effect of the Ge region on the migration of charges is expected to be limited, and no threshold in the induced nonlinearity for short poling time is expected. A couple of gold-coated tungsten electrodes have been placed in holes. Thermal poling has been performed in air atmosphere keeping the temperature at 280°C with 4 kV high voltage applied. In all the fibres the poled length was 7 cm.

Results: A heterodyne Mach-Zehnder interferometer has been used for the EO characterisation of our poled samples. The EO coefficient r in such configuration depends on the measurable ratio ΔI_{dB} between the carrier frequency and the sideband peak intensities as shown in (1):

$$r = 2^{1/2}\left[\frac{n_0^3}{2k_0 L E_m}\right]10^{(\Delta I/20)} \qquad (1)$$

where k_0 is the vacuum wave vector, n_0 the fibre effective refractive index and the modulating electric field over a length L, corresponding to an applied voltage $V(t)$ at angular velocity Ω, is given by

$$E(t) = E_m \cos(\Omega t) \qquad (2)$$

A typical spectrum analyser curve (Fig. 2) was obtained with the twin-holed thermally poled fibre. The measured $\Delta I_{dB} = 60$ dB corresponds to an EO coefficient $r = 0.2$ pm/V and $\Omega = 3.5$ kHz. Fig. 3 shows the trend for the EO coefficient in the Ge-doped fibre. The former presents a peak in intensity after 10 min thermal poling, and a maximum value of 0.082 pm/V is recorded. As expected, due to the small anode-core distance, no threshold in the nonlinearity for short poling time is observed. The existence of a maximum in the second-order optical nonlinearities after thermal poling in the germano silica fibres has been experimentally observed, as long as the trapping of charges during the ionic migration under the applied electric field is absent or negligible.

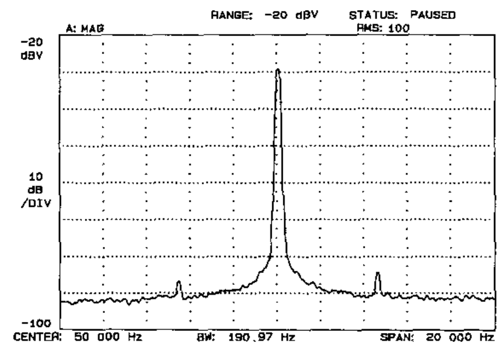

Fig. 2 *RF spectrum from heterodyne Mach-Zehnder interferometer*

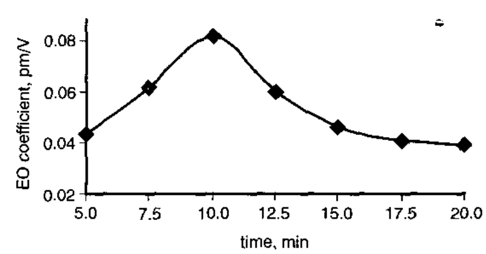

Fig. 3 *Evolution with poling time of electro-optic coefficient in Ge core twin hole fibre poled at 280°C and 4 kV*

Discussion: A one-ion species drifting model [2] cannot explain our experimental results where a fast intensification of the optical nonlinearity is followed, after reaching a peak, by a drop off to lower values. Instead, the two-charge ion drifting model has the advantage of being able to describe, even in this case, the experimental evolution of the nonlinear coefficient and the internal values of the electric field induced during thermal poling in the silica fibre.

In a two-charge configuration, apart from the sodium impurity concentration, the hydrogen ion needs to be taken into account [3]. Indeed, in the case of a twin hole fibre, the metal electrodes will not stop the diffusion of hydrogen ions under the applied electric field from the atmosphere into the fibre. The mobility μ_H, corresponding to the carrier H^+, is in the range 10^{-4}–10^{-3} μ_{Na} (μ_{Na} is the Na^+ mobility). It is clear that when the sodium impurities move, there will be firstly a depleted region under the anodic area followed by a neutral region, and then when the influence of the moving H^+ is stronger, the latter will substitute the Na^+ just under the anode.

In a fibre schematic model of the ions motion under the applied field, we have first a fast Na^+ migration leading to the initial expansion of a depletion layer and then a slower motion of ions associated with lower mobility. We have proved that the high germania content in the fibre core corresponds to a barrier for ions with lower energy. We presume then that the ions during the initial fast depletion growth will have enough energy to break through the Ge-doped layer. If the core is too far from the anode, the indiffusing H^+ ions will slow down the first migrating charges and the nonlinearity can be stopped before passing through the core region. If there is sufficient overlap between the fibre core and the nonlinear region, the EO effect can be strong enough to modulate the transmitted light.

Conclusion: We have presented some measurements on the EO coefficient of thermally poled fibres using an heterodyne Mach-Zehnder interferometer. The nonlinearity dynamics with the poling time for a Ge-doped core fibre has been given. According to our results, a first rapid growth to a maximum of the EO coefficient is followed by a decay to lower values. The experimental results have been explained considering that a two-charge carrier model can account for the trend in the curve. We believe that these results are significant in order to optimise the overlap of the frozen electric field spatial distribution with the two propagating modes (fundamental and SH) and to enhance the nonlinearity properties in thermally poled fibre devices.

5 October 2002
Electronics Letters Online No: 20030061
DOI: 10.1049/el:20030061

A.C. Busacca (*Dipartimento d'Ingegneria Elettrica, Viale delle Scienze—Parco d'Orleans, Università degli Studi di Palermo, Palermo 90128, Italy*)

E-mail: busacca@unipa.it

D. Faccio (*Pirelli Laboratories, Optical Innovation, Viale Sarca 222, 20127, Milano, Italy*)

References

1 ALLEY, T.G., BRUECK, S.R.J., and MYERS, R.A.: 'Space charge dynamics in thermally poled fused silica', *J. Non-Cryst. Solids*, 1998, **242**, pp. 165–176

2 VON HIPPEL, A.: 'Photocurrent in alkali halide crystals', *Phys. Rev.*, 1953, **91**, pp. 568–579

3 KRIEGER, U.K., and LANFORD, W.A.: 'Field assisted transport of Na^+, Ca^{2+} ions and electrons in commercial soda lime glasses', *J. Non-Cryst. Solids*, 1988, **102**, pp. 50–61

Theory of optimal power budget in quasi-linear dispersion-managed fibre links

S.K. Turitsyn, M.P. Fedoruk, V.K. Mezentsev and E.G. Turitsyna

A theory of an optimal distribution of the gain of in-line amplifiers in dispersion-managed transmission systems is developed. As an example of the application of the general method, a design of the line with periodically imbalanced in-line amplification is proposed.

Introduction: It is a common practice in the design of modern transmission systems to set the gain of in-line optical amplifiers to compensate for the loss of the preceding fibre span. This is not always the best choice, as we demonstrate in this Letter.

The performance of many fibre transmission systems is determined by a trade-off between noise and nonlinear impairments. The effects of noise can be estimated through the level of the signal-to-noise ratio (SNR) at the receiver. There is no similar clear parameter indicating the impact of nonlinearity; however, using a 'linear approach' (assuming that nonlinearity is always bad for transmission [private communication]) we can consider the nonlinear phase shift as a measure of the corresponding impairments [1, 2]. Note that such a measure could require some reconsideration and modification for systems making positive use of nonlinearity. In this Letter, however, we assume that the nonlinear phase is an accurate parameter to assess transmission system performance [1]. Based on this assumption we develop a theory of power budget optimisation in dispersion-managed cascaded optical amplifier systems. The theory presented is a generalisation of the approach suggested by Mecozzi (for uniform fibre lines) in his pioneering work [3] to the case of arbitrary DM lines. Applying our general results to a specific configuration we propose a novel design of the transmission system with periodically imbalanced in-line amplification.

Theory: The optimal input signal power maximises the output SNR keeping the overall nonlinear phase shift fixed or vice versa minimises the nonlinear phase for a given SNR. It is of practical interest to be able to reduce some effective average signal power without degradation of the SNR.

Consider a chain of different fibre segments and optical amplifiers. Using the notation introduced in [3], let G_k, $k = 1, 2, 3, \ldots, N$, be the gain of the kth amplifier, $\Gamma_k = \exp[-\gamma_k L_k]$, $k = 1, 2, 3, \ldots, N$ be the loss of the fibre segment before the kth amplifier and the power P_k, $k = 2, 3, \ldots, N$ be the output of the $(k-1)$th amplifier. Here P_1 denotes the input signal power and $P_{N+1} = P_{out}$ is the output power of the last amplifier playing the role of a receiver preamplifier. The accumulated amplified spontaneous emission (ASE) power at the output of the system, integrated over the signal bandwidth B is $P_{ASE} = n_{sp} v h B \sum_{k=1}^{N} (G_k - 1)(T_N/T_k)$ where n_{sp} is the excess noise factor, v is the signal frequency, h is Planck's constant and T_k is the power transmission from the line input to the output of the kth amplifier $T_k = 1$, $k = 0$; $T_k = \Pi_{m=1}^{k} G_m \Gamma_m$, $k = 1, 2, 3, \ldots, N$. The output SNR then takes the form $1/\mathrm{SNR}_{out} = n_{sp} h v B [\sum_{k=1}^{N} 1/P_k (1/\Gamma_k - 1 + \delta_{k,1}) - 1/P_{out}]$. An important difference from the work [4] is that in DM systems fibre parameters vary from span to span (in particular, effective area and loss). Therefore, the accumulated nonlinear phase rather than the average power is an appropriate characteristic of the signal distortion due to nonlinearity. The explanation of this fact is rather transparent. In the estimate of the overall signal distortion due to nonlinearity it is not only the average power that matters, but also the spot size (the fibre effective area) where this power is concentrated during propagation. In DM lines built from different fibres this issue must be taken into account in optimisation of the power budget.

Let us now calculate the nonlinear phase shift along the amplifier span. The power variation along the kth fibre span is: $P_k(z) = P_k \exp[-\int_0^z dz' \gamma_k(z')]$. Here $\gamma_k(z)$ is the loss coefficient of the kth fibre segment and P_k is the power at the output of the $(k-1)$th amplifier. The power averaged over the segment of length L_k can be written as $\int_0^{L_k} dz P_k(z) = P_k \Lambda_k$, where an effective nonlinear interaction length Λ_k [4] of the kth fibre segment is: $\Lambda_k = \int_0^{L_k} dz (n_2/A_{eff}^k(z)) \exp[-\int_0^z dz' \gamma_k(z')]$. The total accumulated nonlinear phase shift over the link of the length L_{tot} is then calculated as $\Phi_{NL} = L_{tot} \sum_{k=1}^{N} P_k \Lambda_k$. Applying now the method of Lagrange multipliers to minimise the nonlinear phase shift under the fixed output SNR we get (omitting straightforward calculations for the sake of space)

$$G_k = \sqrt{\frac{\Lambda_k (1 - \Gamma_{k+1})}{\Lambda_{k+1} (1 - \Gamma_k) \Gamma_k \Gamma_{k+1}}}$$

Here it is assumed that the power is recovered at the end of the link, $P_{out} = P_{N+1} = P_1$. The input power is then expressed through the line parameters and (fixed) output SNR:

$$P_1 = \mathrm{SNR}_{out} n_{sp} h v B \sqrt{\frac{1 - \Gamma_1}{\Lambda_1 \Gamma_1}} \sum_{k=1}^{N} \Lambda_k^{1/2} \left(\frac{1}{\Gamma_k} - 1 \right)^{1/2}$$

In-line powers P_k can be found from the relation $P_{k+1} = \Gamma_k G_k P_k$. The same result holds if we require a maximal output SNR under the restriction of the fixed overall nonlinear phase shift.

Lines with periodically imbalanced amplification: As a particular example, we use the above general theory to design a transmission