Direct measurement of pump-induced phase modulation in erbium-doped fibres

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ing spectrum with increasing of the pumping current. Within the limits of the free-running cw generation regime (I_p = 120 mA), no evidence of chirping in the spectrum is observed. The modal chirp appears when passing to the mode-locking regime (I_p = 130 mA), and its value increases with pumping current. As mode-locking develops, the laser spectrum becomes markedly asymmetric (I_p, > 150 mA). This effect can be explained by the fact that the dispersion of the laser active medium decreases with wave-length. The minimal value of time-bandwidth product ΔΔν/ν = 0.52 was registrated. It should be noted that the optical pulses obtained are not transform-limited ones due to the chirp effect and it is possible to compress them in a medium with a proper dispersion. With further increase in pumping current (I_p = 170 mA), the lasing spectrum broadens (with the corresponding increase in the time-bandwidth product) and becomes symmetric again, which is supposedly due to gain saturation for longer wave-length modes.

An important advantage of the lasers investigated is that their entire spectrum lies in the amplification band of erbium-doped fibers. Being combined with fiber amplifiers, these lasers could serve as a source of soliton pulses with a very high repetition rate. It should be also noted that the measurement of laser characteristics being carried out during approximately 50 hours of operation under cw pumping and no degradation of spectra or parameters was observed.

CW passive mode-locking was observed for the first time in InGaAsP laser diodes with saturable absorber regions created by the ion implantation. Optical pulses of 650 fs width at 110-GHz repetition rate were obtained in a spectral range of 1.53–1.54 μm. No changes in spectra and autocorrelation traces were observed after 90 hours of cw operation.

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Dynamics and origin of the optical Kerr effect in CdSe nanoparticles in the resonant regime
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In the resonant regime, the optical Kerr effect of CdSe-doped glasses is due to photoexcitation of carriers whose presence modifies the optical properties of the CdSe quantum dots. The recovery time, which governs the reproduction rate at which such devices could be operated, is equal to the recombination time of these carriers. At low laser intensity, the recombination may be timed by the Auger effect, which is a quadratic one.

Using three different time-resolved techniques, optical phase conjugation, nonlinear absorption, and time-resolved luminescence, we clearly observed that, for a fresh sample, at high laser intensity and for not too long delay times, carrier recombination is dominated by Auger processes. All these data lead to an Auger constant on the order of a few 10^-12 cm^2 s^-1. When the sample has been photo-darkened, both the linear nonradiative decay and the Auger process are important.

Understanding the origin of the nonlinear properties in these media is also of importance since such artificial materials can, in principle, be tailored to meet specific requirements. The optical Kerr effect may be due to free carriers in which case it corresponds to saturation of the first electronic transition and to induced absorption between the corresponding one-pair state and two-pair states. Alternatively, the photoexcited carriers may be trapped at the surface of the nanoparticles and, through the static electric field they create for example, they may also modify the optical properties.

Time resolving the nonlinear response at low laser intensity and in the degenerate case for samples having experienced various degrees of photodarkening, we have been able to access the relevant mechanisms. Usually, the response shows both a fast component due to free carriers and a slow one due to trapped carriers. The larger the darkening dose is, the smaller the time constant of the fast component and the smaller the magnitude of the slow component. The dominant mechanism is thus observed to depend on the origin of the sample and on its past history. Time-resolving the nonlinear response is the most reliable technique of determining it.


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Direct measurement of pump-induced phase modulation in Er-doped fibres
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A system, which is able to determine pump induced phase modulation in Er-doped fibres for phase shifts φ_p ranging from -π/20 to several π, has been developed. The system (see Fig. 1) consists of a Mach–Zehnder interferometer using a polarization maintaining 3-dB fibre coupler. One arm of the interferometer includes an Er-doped fibre pumped by a 980-nm Ti:sapphire laser. Light from a tunable semiconductor signal laser (λ_s = 1.5 μm ± 1.6 μm) is coupled to both interferometric arms. A differential detection scheme improves the sensitivity and eliminates influence of amplified spontaneous emission. The phase in the reference arm is linearly modulated in time, φ_s = ω t, by means of a piezo-electric crystal. This results in a response of the detected signal, which in the case of no pump power can be written:

\[ Δφ = \cos(ω t + φ_p), \]

and in presence of pump power:

\[ Δφ = \cos(ω t + φ_p + φ_0), \]

where φ_0 is an arbitrary phase and φ_p is the pump-induced phase shift of the signal. φ_p is determined by measuring the phase difference of the cosine waveforms before and after the pump is turned on by an optical chopper.

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Fig. 1. Schematic of the setup for directly measuring pump-induced phase modulation in Er-doped fibres.
Er-doped fibres with a do in symbols), 2

QThF2 Fig. 2. Refractive index change as function of wavelength for Er-doped fibres with doping concentrations of $0.7 \times 10^{19}$ cm$^{-3}$ (square symbols), $2 \times 10^{19}$ cm$^{-3}$ (cross symbols), and $8 \times 10^{19}$ cm$^{-3}$ (triangular symbols). The pump power at 980 nm is 4 mW.

QThF2 Fig. 3. Refractive index change as function of absorbed pump power for Er-doped fibres with doping concentrations of $0.7 \times 10^{19}$ cm$^{-3}$ (square symbols) and $8 \times 10^{19}$ cm$^{-3}$ (triangular symbols) at different wavelengths as indicated.

In Fig. 2, the change in refractive index defined as, $\Delta n = \Delta n_s/\Delta n_{bkg}$, where $L$ is the length of the fibre, is plotted for three fibres with Er$^{3+}$-doping concentrations of $1.7 \times 10^{19}$ cm$^{-3}$ (square symbols), $2 \times 10^{19}$ cm$^{-3}$ (cross symbols) and $8 \times 10^{19}$ cm$^{-3}$ (triangular symbols) as function of wavelength at an absorbed pump power of 4 mW. The $\Delta n$ increases with increasing doping concentration and changes sign at $\lambda_{1} = 1535$ nm, which is situated just below a resonance wavelength of 1530 nm. The slope of the curves and therefore the dispersion are maximum near resonance. The dispersion for the fibre with the highest doping concentration is calculated to be $200$ ps/nm/km at 1530 nm.

Figure 3 shows $\Delta n$ as function of absorbed pump power for the fibres with Er$^{3+}$-concentrations of $0.7 \times 10^{19}$ cm$^{-3}$ (square symbols) and $8 \times 10^{19}$ cm$^{-3}$ (triangular symbols). The wavelengths depicted in Fig. 3, $\lambda_{1} = 1565$ nm and 1568 nm are situated below resonance and the wavelengths $\lambda_{2} = 1522$ nm and 1520 nm are situated above resonance, where a larger $\Delta n$ can be obtained. The $\Delta n$ saturates at higher pump powers for the fibre with the higher doping concentration. Thermal effects are believed to be negligible, since a thermal contribution to $\Delta n$ should be either positive or negative and independent of wavelength, in contrast to the results shown in Fig. 3.

The proposed system has proven to be useful to measure pump-induced phase shifts directly and refractive index changes in Er-doped fibres. The results show that a highly doped fibre should be used if refractive index modulation is desirable (e.g., in optical switches). In applications where the dispersion is unwanted (e.g., in soliton transmission systems), a tradeoff between gain and refractive index modulation should be made for the operating wavelength. *Lecom A/S, NKT Alle 75, 2605 Brondby, Denmark*

QThF3 Fig. 1. Output energy versus input energy and best fit (solid curves). Femtosecond data at 605 nm.

QThF3 (limited) 1130 Two-photon absorption of semiconductor crystallites in doped glasses

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One of the questions concerning semiconductor doped glasses (SDG) is whether the nonlinearities of the crystallites at frequencies well below bandgap are affected by the electronic confinement. The problem has both conceptual and practical implications. Large effects even for modest confinement have been suggested by theoretical models, but the data so far reported are not conclusive to this regard. We here report the first quantitative determination of $\beta_{2}$.

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In order to obtain $\beta_{2}$, one derives, through a nonlinear transmission measurement, $\beta_{2}$ the two-photon absorption (TPA) coefficient of the SDG. $\beta_{2}$ is related to $\beta_{2}$ through $\beta_{2} = (\omega^{2}e^{2}e^{2})^{-1} Im \chi^{(3)}$ and then makes use of the relation $\chi^{(3)} = \chi^{(3)} + \chi^{(2)}$, where $\chi^{(2)}$ is the local field correction factor, and $\chi^{(3)}$ the volume fraction occupied by the crystallites. The crucial quantities in the procedure are $\beta_{2}$ and $\chi^{(2)}$.

Since the volume fraction cannot be obtained neither from a wet analysis, nor from the initial composition of the SDG, we plotted the scaled quantity $(\omega/e_{0})^{2} Im \chi^{(3)}$ for bulk semiconductors.

Two-photon absorption:

Elettronica, Università di Pavia, Via Ariosto 209, Pavia, Italy

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