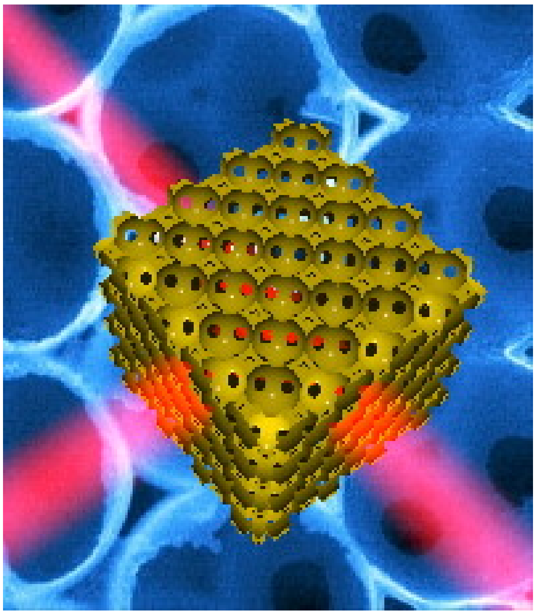
INTERNATIONAL WORKSHOP ON NONLINEAR PHOTONIC CRYSTALS

Technical University of Denmark

Kgs. Lyngby, Denmark

October 25-26, 2001



Conference organizer:

Ole Bang

Department of Informatics and Mathematical Modelling

Technical University of Denmark, 2800 Kgs. Lyngby, Denmark

Sponsored by the Danish Graduate School in Nonlinear Science

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PROGRAM

Thursday, October 25, 2001 :

08.30-	Registration and reimbursement - Hanne Jensen	Outside Aud. 053, bldg. 305
09.00-09.05	Opening by Ole Bang	Aud. 053, bldg. 305
09.05-09.50	Kurt Busch, *Photonic bandstructure computation meets optical nonlinearity*	Aud. 053, bldg. 305
09.50-10.10	Lasha Tkeshelashvili, *Sum frequency generation in photonic crystals*	Aud. 053, bldg. 305
10.10-10.40	Coffee and tea break	Outside Aud. 053, bldg. 305
10.40-11.25	Min Qiu, *Photonic crystal waveguides and cavities in integrated optics*	Aud. 053, bldg. 305
11.25-12.10	Sergey Bozhevolnyi, *2D interface photonic crystals color for surface plasmon polaritons*	Aud. 053, bldg. 305
12.10-13.40	Lunch break	Cafeteria, bldg. 101
13.40-14.25	Sergei Mingaleev, *Nonlinear localized modes in photonic crystals and photonic crystal waveguides*	Aud. 053, bldg. 305
14.25-14.45	Rumen Iliew, *Light propagation through coupled defects in photonic crystals*	Aud. 053, bldg. 305
14.45-15.30	Poster session with coffee and tea	Outside Aud. 053, bldg. 305
15.30-16.15	Burak Temelkuran, *Guiding, bending and splitting of electromagnetic waves in photonic crystal waveguides*	Aud. 053, bldg. 305
16.15-16.35	Mikael Mulot, *Fabrication of low index contrast semiconductor based photonic crystals*	Aud. 053, bldg. 305
16.35-17.30	Evening beer	Outside Aud. 053, bldg. 305
18.00-	Workshop dinner	Big Mamma's Pizza House, Jernbanegade, Kgs. Lyngby

Friday, October 26, 2001 :

08.30-	Registration and reimbursement - Hanne Jensen	Outside Aud. 053, bldg. 305
09.05-09.50	Ole Bang, *Asymmetric cubic nonlinearities induced by long period gratings: Signature and importance*	Aud. 053, bldg. 305
09.50-10.10	Joel Corney, *Modulational instability and solitons in long-period $\chi^{(2)}$ gratings*	Aud. 053, bldg. 305
10.10-10.40	Coffee and tea break	Outside Aud. 053, bldg. 305
10.40-11.25	Roland Schiek, *Experiments on solitons and MI in QPM crystals*	Aud. 053, bldg. 305
11.25-12.10	Anders Bjarklev, *Photonic crystal fibres and the company Crystal Fibre A/S*	Aud. 053, bldg. 305
12.10-13.40	Lunch break	Cafeteria, bldg. 101
13.40-14.25	Tanya Monro, *Microstructured fibres: moulding the properties of light*	Aud. 053, bldg. 305
14.25-14.45	Vittoria Finazzi, *Modelling confinement loss in practical small-core holey optical fibres*	Aud. 053, bldg. 305
14.45-15.30	Poster session with coffee and tea	Outside Aud. 053, bldg. 305
15.30-16.15	Stephane Coen, *Supercontinuum generation in photonic crystal fibres*	Aud. 053, bldg. 305
16.15-16.35	Kentaro Furusawa, *Development and applications of ytterbium-doped highly nonlinear holey optical fibres*	Aud. 053, bldg. 305
16.35-	Evening beer	Outside Aud. 053, bldg. 305

PHOTONIC BANDGAP MATERIALS

Thursday, October 25, 2001

Photonic bandstructure computation meets optical nonlinearity

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Photonic Crystals (PCs) represent a novel class of optical materials where Bragg-scattering of electromagnetic waves at periodic modulations of the refractive index of these microstructured materials leads to the formation of a photonic bandstructure. As a consequence, the judicious design of these materials allows the tailoring of photonic dispersion relations and corresponding mode structures which, in turn, opens entirely new avenues for both basic research as well as technological applications.

With PCs it thus becomes possible to manipulate the radiation dynamics of active materials embedded in them as well as the propagation characteristics of electromagnetics radiation. In fact, the seminal papers of Yablonovitch [1] and John [2] have been concerned with the possibility of inhibiting spontaneous emission [1] and the realization of Anderson-localization of light [2] in PCs, respectively. Since then, numerous novel effects regarding the radiation dynamics of active materials such as fractional localization near a photonic band edge [3] and all-optical transistor action [4] have been proposed. Similarly, the re-examination of classical nonlinaer effects such as nonlinear susceptibilities [5], and soliton propagation [6] in PCs have revealed a number of interesting results that await experimental confirmation.

In this presentation, we will give an introduction to photonic bandstructure computation with an emphasis on photonic bandstructure theory as a predicitve as well as interpretative tool for nonlinear optical effects in PCs. First, we will discuss the plane wave method (PWM) and its application to PCs whose constituent materials exhibit tunable electro-optical anisotropies [7]. The resulting tunability of the photonic bandstructure may greatly enhance the utility of these systems over and above conventional PCs as well as homogeneous electro-optical materials. Next, we describe a recently developed multigrid method (MGM) for photonic bandstructure computations [8]. This real space approach allows the efficient determination of photonic modestructures and avoids the PWM-inherent problem of truncating Fourier series. As a consequence, MGM is much better suited to the calculation of quantities that are relevant to nonlinear phenomena in PCs such as group velocities and effective nonlinearities. Finally, we will outline how the slowly varying envelope approximation may be generalized to the description of nonlinear phenomena in PCs. This may be achieved through combining elements from kp-perturbation theory of electronic semiconductors with a multi-scale analysis of the electromagnetic wave equation where the eigenmodes of the (linear) PC, the Bloch functions, represent the carrier waves.

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Sum frequency generation in photonic crystals

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Progress in photonics is closely connected to the development of optical materials with tailor made properties. In the context of nonlinear optical phenomena, Photonic Crystals (PCs) carry this principle to a new level in that the tailoring of the dispersion relation and mode structure allows to explore regimes for parameters such as group velocities, group velocity dispersion and effective nonlinearities which have hitherto been virtually inaccessible.

Any succesfull experimental exploration of the huge parameter space provided by PCs has to be accompanied by a quantitative theoretical analysis in order to identify the most interesting cases and to help interpret the data. To date, only a few works along these lines has been carried out for either Kerr-nonlinearities [1] or sum-frequency and second harmonic generation [2]. Moreover, the approximations involved seriously limit the applicability of these theories to real PCs. For instance, the study of Kerr-nonlinearities in two-dimensional PCs [1] has been limited to the nearly free photon case, i.e., weak modulations in the linear index of refraction. Similarly, the recent investigation of second harmonic generation in two-dimensional PCs [2] failed to reproduce the well-known results for the limiting case of a homogeneous material.

In this presentation, we will apply the multi-scale analysis to the case of sum-frequency generation in two-dimensional PCs and discuss some of the most interesting results. In particular, we show how the PC allows to access experimentally a parameter range that has been considered theoretically by Zakharov [3]. For instance, as there are no stable soliton solutions in two dimensions, a two-dimensional PC would allow the complete radiation conversion from one wavelength to another through nonlinear interactions. This may have important applications for wavelength shifters in telecommunication technology.

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Photonic crystal waveguides and cavities in integrated optics

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Two-dimensional Photonic Crystal (2D PC) waveguides and cavities are key elements in photonic crystal based integrated optics. Devices based on 2D PCs are typically realized as 3D structures consisting of an array of holes (or rods) vertically etched through a slab waveguide. The existence of holes in a slab waveguide may induce strong radiation losses to the slab claddings. By employing the 2D finite-difference time-domain method, and the effective-index method to account for the vertical confinement, we show that a remarkably good agreement with experiments can be obtained, for a number of experimentally studied PC structures (cavities, waveguides and bends). Many of PC waveguides are multi-mode, thus the coupling between the different guided modes are of interest. Mode-gaps (or mini-stop-bands) may arise from Bragg diffraction of the incident mode into the counter-propagating modes. In the talk, we also present the experimental characterization and theoretical calculations of mini-stop-bands, which are important to accurately design and fabricate PCs.

2D interface photonic crystals for surface plasmon polaritons

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The interest in photonic crystals (PCs) has dramatically risen since the possibility of efficient waveguiding around a sharp corner of line defect in a PC has been pointed out. This property of PC-waveguides opens the perspective of designing photonic circuits with an unprecedented level of integration. The idea is to confine the radiation in one dimension (e.g., by using a planar waveguide) and to control its propagation by 2D periodic modulation of refractive index. However, such a configuration is only quasi-2D, and there exists a formidable problem of keeping the radiation in the waveguide plane, especially that propagating along PC-waveguides. Recently, we have suggested the usage of special interface waves, viz., surface plasmon polaritons (SPPs), for the same purpose [1]. SPP's are surface electromagnetic waves propagating along a metal-dielectric interface and having the amplitudes exponentially decaying in the neighbor media. One can achieve periodic modulation of the SPP propagation constant by varying the refractive index of dielectric and/or metal or by changing the interface profile. Here the results of experimental investigations concerning SPP waveguiding along line defects in periodically corrugated surfaces of gold films [2,3] are presented and illustrated with theoretical simulations.

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Nonlinear localized modes in photonic crystals and photonic crystal waveguides

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Photonic crystals are usually viewed as an optical analog of semiconductors that modify the properties of light similarly to a microscopic atomic lattice that creates a semiconductor band-gap for electrons. It is therefore believed that by replacing relatively slow electrons with photons as the carriers of information, the speed and band-width of advanced communication systems will be dramatically increased, thus revolutionizing the telecommunication industry. However, to employ the high-technology potential of photonic crystals, it is crucially important to achieve a dynamical tunability of their properties. This idea can be realized by changing the light intensity in the *nonlinear photonic crystals.*

Here, we develop the theory of nonlinear localised modes in two-dimensional photonic crystals and photonic-crystal waveguides. We demonstrate that such nonlinear localised modes can be accurately described by a new type of discrete nonlinear Schroedinger equation with long-range interactions.

Using this approach, we consider different geometries of the photonic-crystal waveguides created by an array of nonlinear dielectric rods embedded into an otherwise perfect linear two-dimensional photonic crystal; we reveal the existence of different types of nonlinear guided mode and describe their unique properties, including bistability.

We also predict stabilisation of the two-dimensional nonlinear localised modes near the band edge of a reduced-symmetry photonic crystal with a Kerr nonlinearity.

More information about our research on nonlinear photonic crystals can be found on the page: http://wwwrsphysse.anu.edu.au/nonlinear/research/photonic

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Light propagation through coupled defects in photonic crystals

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Efficient waveguiding around sharp bends is a key task in microoptics. Using the reciprocity theorem we derive coupled-mode equations for light propagation in coupled-defect waveguides. This can applied to arrays of defects in two-dimensional photonic crystals and three-dimensional photonic-crystal slabs. Modes were calculated numerically and overlap integrals were calculated from these results to obtain the coefficients for the equations of motion for different configurations. The dispersion relations resulting from these coupled-mode equations are compared to the dispersion relations obtained from bandstructure calculations of the real structure. We consider the case of multi-moded defects and the case where the isolated defect is single-moded. In the two-dimensional case the validity of the model is checked by means of finite-difference time-domain calculations.

Guiding, bending and splitting of electromagnetic waves in photonic crystal waveguides

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We have investigated the guiding, bending and splitting of electromagnetic (EM) waves in three different types of waveguides built around layer-by-layer photonic crystal structures at microwave frequencies: planar waveguide, coupled cavity waveguide and highly confined hallow waveguide.

Introducing an air gap between two photonic crystal walls, we observed full transmission of the guided electromagnetic (EM) waves within the stop-band frequencies of the photonic crystal through this planar waveguide structure. We used two different methods to explain the guidance of the EM wave: The first approach was to use the phase difference, introduced by the guide, to calculate the dispersion relation. In the second method, calculating the effective width of the guide from the reflection-phase measurements of the photonic crystal walls, we used a planar waveguide theory to achieve the same dispersion relation. The results of both methods were in good agreement with each other, and were powerful in predicting the frequencies at which the guidance starts and ends. We then coupled the output of this planar waveguide into a second planar waveguide, which was perpendicular to the first. The EM wave, making a 90 degrees turn through the guides, resulted in an average transmission of 10 dB below the incident signal, within the stop-band frequencies of the photonic crystal.

The eigenmode splitting due to coupling between the evanescent defect modes was observed experimentally and well explained by the classical wave analog of the tight-binding (TB) method in the solid state physics. Forming the cavities by removing a single rod from each unit cell of a layer-by-layer dielectric photonic crystal, we were able to extract the TB parameters from the experimental results. We used these coupled cavities to demonstrate a new type of waveguiding mechanism in three-dimensional photonic crystals. In this waveguide, photons propagate through strongly localized high-Q cavities via hopping. High transmission of the electromagnetic waves, nearly 100placed along an arbitrarily shaped path. The dispersion relation of the waveguiding band is obtained from transmission-phase measurements, and this relation is well explained within the tight-binding photon picture.

We constructed another waveguide structure by removing rods, where in this case, the hallow region formed by the removed rod was used as the waveguide. Full transmission of the EM waves was observed for straight and bended waveguides. We also investigated the power splitter structures in which the input EM power could be efficiently divided into the output waveguide ports. The experimental results, dispersion relation and photon lifetime, were analyzed with a theory based on the tight-binding photon picture.

We proposed and demonstrated two other methods to split electromagnetic waves based on the waveguide structures described above. By measuring transmission spectra, it was shown that the guided mode in a coupled-cavity waveguide can be splitted into the coupled-cavity or planar waveguide channels without radiation losses. The flow of electromagnetic waves through output waveguide ports can also be controlled by introducing extra defects into the crystals.

Since the Maxwell's equations have no fundamental length scale, our microwave results can easily be extended to the visible spectrum, where these results may provide important tools for designing photonic crystal based optoelectronic components.

Fabrication of low index contrast semiconductor based photonic crystals

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We demonstrate low-loss photonic-crystal (PC) waveguides realized in InP by Ar/Cl2 based Chemically Assisted Ion Beam Etching. The waveguides are obtained as line defects in a triangular lattice of holes etched through a three-layer InP/GaInAsP/InP heterostructure. By optimizing the etching parameters so that the physical and the chemical components are balanced we succeed in obtaining holes deeper than 2 m even for a hole diameter as small as 220 nm. The quality of the PCs etched by two different process conditions are compared by using the shape and the position of one of the mode-gap as an assessment tool. The measured transmission spectra indicate that the PC waveguides etched with an optimized process exhibit losses smaller than 1dB/100m. This is to date the lowest loss value reported for PC waveguides in semiconductor heterostructures at optical communication wavelengths.

LONG-PERIOD QUASI-PHASE-MATCHING PHOTONIC CRYSTALS

Friday, October 26, 2001

Asymmetric cubic nonlinearities induced by long period gratings: Signature and importance

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Since the observation of nonlinear phase-shifts larger than π, quadratic nonlinear or $\chi^{(2)}$ materials have been of significant interest in photonics. With the maturing of the quasi-phase-matching (QPM) technique, in particular by electric-field poling of ferro-electrics, such as $LiNbO_3$, the potential of $\chi^{(2)}$ materials has increased even more.

In addition to providing effective phase-matching, QPM gratings generate asymmetric cubic nonlinearities (ACN) in the equations for the average field [1,2]. This cubic nonlinearity is focusing or defocusing according to the sign of the phase mismatch [2], and its strength can be engineered by modulating the grating. In CW-operation ACN induce an intensity dependent phase mismatch, which implies a nonzero so-called separatrix intensity, the crossing of which abruptly changes the phase-shift of the fundamental over a period by π [3]. We have found the QPM-induced separatrix intensity and the crystal lengths necessary for an optimal flat phase-versus-intensity response on either side of the separatrix [3].

The best example appears when the competition between a linear and a nonlinear QPM grating eliminates the effective $\chi^{(2)}$ nonlinearity. With no nonlinearity solitons should not exist but, as shown in Fig. 1, stable solitons do exist [2]. This paradox is elegantly explained by including ACN in the model, which then correctly supports simple bright and dark nonlinear Schrödinger solitons. In describing modulational instability, it is also necessary to include the ACN to correctly predict the novel QPM-induced regimes in which long-wave instabilities disappear and plane waves become modulationally stable over hundreds of diffraction lengths [4].

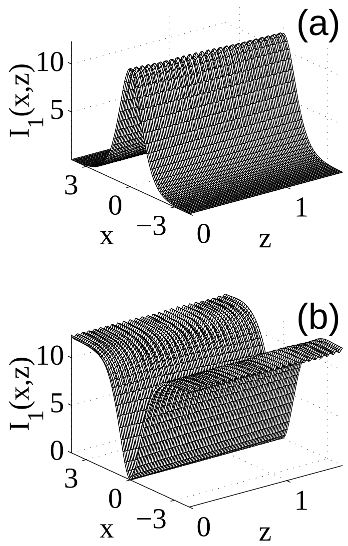

Fig. 1: *Fundamental intensity of (a) bright and (b) dark solitons propagating in a sample in which the QPM grating eliminates the effective $\chi^{(2)}$ nonlinearity.*

ACN are a general effect of non-phase-matched interaction and thus appear also in homogeneous $\chi^{(2)}$ materials (no grating) in the cascading limit [4]. In this case the asymmetric signature of ACN may be measured as the difference between the properties in upconversion and downconversion, since there is no effective quadratic nonlinearity. Such an experiment was just reported [5] and thus ACN have now been confirmed experimentally. This research is supported by the Danish Technical Research Council (Grant No. 26-00-0355).

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Modulational instability and solitons in long-period $\chi^{(2)}$ gratings

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The modulational instability (MI) of waveforms is a fundamental nonlinear phenomenon exhibited by many diverse physical systems, including fluids, plasmas, nonlinear optics, and biomolecular chains. MI is closely associated with self-localized waves, or solitons: MI-induced break up can precipitate bright soliton formation, and conversely, the stability of dark solitons requires the absence of MI [1].

We consider the MI of optical beams in media with a purely quadratic (or $\chi^{(2)}$) nonlinearity, analysing in detail the instability gain spectra when linear and nonlinear quasi-phase-matching (QPM) gratings are present. Because such spectra can now be measured in the laboratory [2], studying their profiles has direct experimental relevance.

We find that, due to the periodicity, novel low- and high-frequency bands appear in the gain spectrum [Fig. 1(a)], each with fundamentally different physical origins. The high-frequency gain bands are a general feature of gain spectra for QPM gratings, related to the inherent MI in the non-phase-matched, gratingless $\chi^{(2)}$) material [Fig. 1(d)]. In contrast, the low-frequency bands depend critically on the modulation depths and periods, and can totally disappear for particular gratings. Induced by the phase-matching periodicities, they are accurately predicted by a simple average theory [Fig. 1(c)].

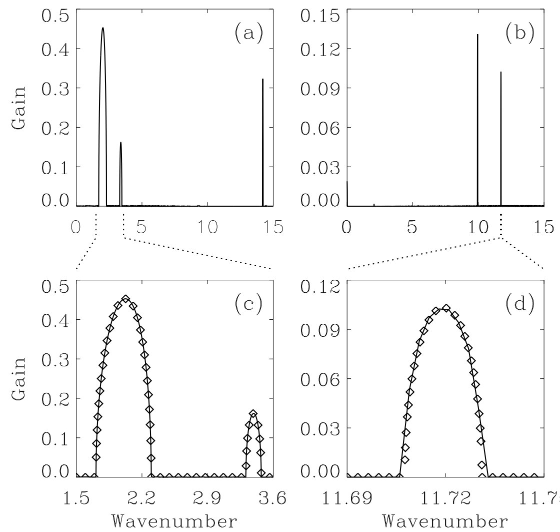

Fig. 1: *Gain spectra for (a) $LiNbO_3$ and (b) GaAs/AlAs gratings. Diamonds give average theory results in (c) and equivalent homogeneous results in (d).*

Our results show that when the low-ν gain bands are suppressed, dark solitons can propagate stably over experimentally relevant distances, due to the residual high-ν gain being typically small. This increases the potential utility of dark solitons in applications, allowing their particular advantages to be exploited [1].

This research is supported by the Danish Technical Research Council through Talent Grant No. 26-00-0355.

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Cascaded nonlinearities in quasi-phase-matched $LiNbO_3$

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The application of second-order optical nonlinearities is no longer restricted to the generation of new frequencies in parametric mixing processes and electro-optics. Nearly a decade ago it was suggested to apply intensity-dependent wave-vector modifications of the interacting waves in a second-order frequency mixing process to realize all-optically controlled light propagation, like soliton formation, all-optical switching and nonlinear spectral broadening. This new aspect of the quadratic nonlinearity is called "cascaded nonlinearity".

An increasing theoretical understanding of the cascaded quadratic nonlinearity and a growing number of numerical simulations of interesting and potential applications has led during the last six years to the performance of a series of experiments which have confirmed the theoretical expectations very well. The first experiments in bulk and waveguide structures investigated mainly the basic physics involved. Intensity-dependent phase shifts were measured. Soliton formation in temporal and spatial dimensions and all-optical switching based on the cascaded nonlinearity were observed. In contrast to the electronic third-order nonlinearity (which supports similar all-optical effects) the quadratic cascaded nonlinearity has the advantage of being more flexible, that it can easily be "engineered", and that it provides new effects like stable two dimensional solitons. Cascading is based on a nonlinear coupling between different travelling waves and can be influenced and adjusted by simple adjustment of the linear wave propagation characteristics of the involved waves. The resulting possibility to adjust the strength and even the sign of the cascaded nonlinearity with temperature or electro-optically was confirmed and characterized in detail experimentally. In view to applications of cascading the fast development of the technology of quasi-phase-matching (QPM) for quadratic nonlinearly coupled waves during the last years has been very important. In lithium niobate for example, the power level for the observation of all-optical effects was reduced from a few thousand to a few ten Watts by replacing birefringent phase-matching with QPM. Furthermore, the possible implementation of spatial inhomogeneous QPM gratings allows to optimize the cascaded nonlinearity in a particular application. For example, the nonlinear loss due to frequency conversion has been minimized with a non-uniform phase-mismatch along the propagation.

Beside being a versatile laboratory for the investigation of nonlinear wave-propagation and dynamics the cascaded nonlinearity has some potential for applications in optical communication systems. Under this point of view, till now, the probably most important experiment demonstrates high-quality multiple-channel wavelength conversion in engineered QPM lithium niobate waveguides. In other very close-to-application experiments the nonlinear phase shifts in cascading were applied for Kerr-lens mode locking and pulse compression. All-optical transistor and diode action based on cascading have been demonstrated. Also quadratic spatial solitons (light-induced waveguides) have an exciting potential for all-optical beam steering and signal routing as well as for beam cleaning. Theory and corresponding soliton interaction experiments have shown that the soliton propagation direction is sensitive to intensity or can be shifted in the interaction with another soliton. A further interesting experimental field is the investigation of modulational instabilities of beams in one or two dimensions for the generation of soliton "arrays". Finally, the very stable and reproducable all-optical switching experiments in directional couplers are worth to be extended. In arrays of coupled waveguides discrete solitons could be used for all-optical and fast signal routing and distribution.

In contrast to a widely spread opinion, recent experiments on mode locking, pulse compression and coupler switching using femtosecond laser pulses have shown that cascading is not inherently limited to narrow bandwidth signals, as it is the generation of new frequencies due to phase-matching constraints. More experimental investigations of the potential of cascading for sub-picosecond data processing are on the way.

PHOTONIC CRYSTAL FIBRES

Friday, October 26, 2001

Photonic crystal fibres and the company Crystal Fibre A/S

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In 1987, it was suggested that the electronic bandgaps in semiconductors could have an optical analogy - the so-called photonic bandgaps (PBGs), which could be found in periodic dielectric structures. This suggestion initiated research activities, which over the past few years have lead to a new class of optical fibers, in which the cladding structure consist of a periodic system of air holes in a matrix of dielectric material - typically silica. These fibers have been given several names ranging from holey fibers, microstructured fibers, photonic crystal fibers, to photonic bandgap fibers. These fibers have today reached a level of maturity where they may be used as building blocks for a variety of new applications. Hence, from focusing on the basic photonic crystal fiber itself and its special way of guiding light, today's research is turning towards applications of the fibers. Some of the new applications that are receiving a significant amount of attention are based on nonlinear effects - super continuum generation and applications of such being highly studied examples. In this presentation, we will firstly discuss the basic properties of photonic crystal fibers and highlight their unique features. Secondly, we will point towards the future of this technology and address a number of potential applications of the fibers.

Microstructured fibres: moulding the properties of light

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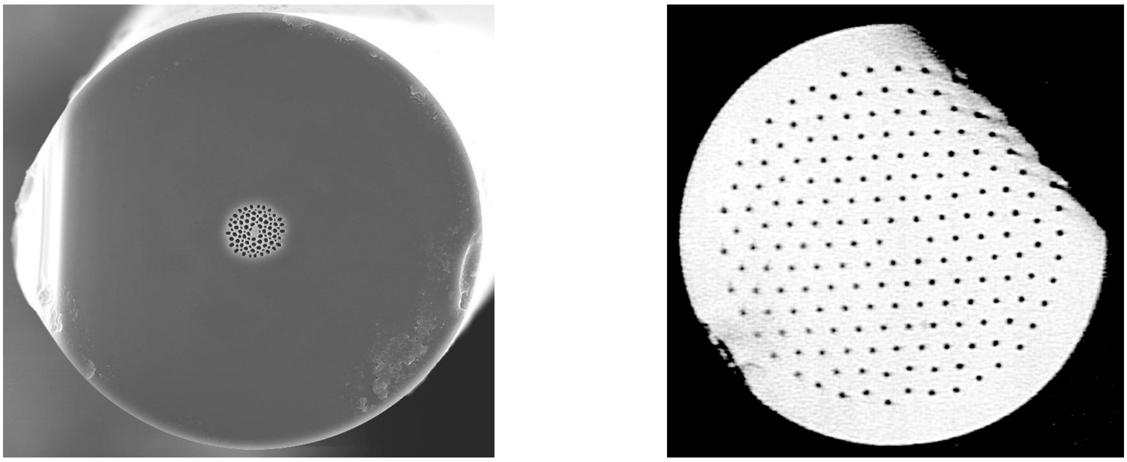
The combination of wavelength-scale features and geometric flexibility offered by microstructured or holey optical fibres (HFs) leads to a significantly broader range of optical properties than is possible in conventional optical fibres (see the examples in Figure 1). These properties include single-mode guidance at all wavelengths, novel dispersion properties including broadband dispersion flattening and anomalous dispersion at visible wavelengths, mode size tailoring over three orders of magnitude, and many more. The optical properties of holey fibres are determined by the size, shape and locations of the air holes that define the cladding region. HFs can be made either from a single material (eg pure silica) or can be doped, which allows active fibre devices to be made.

Progress in this rapidly emerging technology will be reviewed, ranging from modelling and fabrication through to applications and practical devices.



(a) (b)

Fig. 1: *Some typical holey fibre profiles: (a) A holey fibre with a small core (1.5 microns in diameter) provides tight mode confinement and enhanced nonlinearity (b) A large mode area holey fibre (core diameter approx 15 microns) for high power delivery.*

Modelling confinement loss in practical small-core holey optical fibres

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Microstructured optical fibres (MOFs) are all-silica fibres that guide light by means of an arrangement of air-holes that run down the entire fibre length. In the kind of MOFs here considered, also named holey fibres (HFs), guidance arises from average-index effects: the holes form the cladding region around the solid core. The modes of such fibres are leaky because the core refractive index is the same as the index beyond the (finite) cladding region. HFs with a core diameter of the scale of an optical wavelength and large holes have been fabricated, resulting in the smallest effective area ever measured in a fibre at 1550nm [1]. Such small effective areas make these fibres attractive for nonlinear applications. The cladding of a HF is usually comprised of hexagonally-packed rings of holes, and when the hole-to-hole spacing (Λ) is of the order of the wavelength, several rings of holes are required to reduce the confinement loss to a practical value. Fibre fabrication feasibility on the other hand constrains the number of rings that can be used. Therefore in order to optimise the design of this class of fibres, it is necessary to study the loss characteristics for small-core HFs.

To perform this study we applied the multipole method recently developed in Ref. [2]. This method considers MOFs with a finite cladding region of circular holes and performs full-vector modal calculations. This method yields the complex propagation constant, and thus the confinement losses can be calculated via the imaginary part. It uses polar coordinate systems centred in every hole, therefore no-false birefringence is introduced and the symmetry properties of the structure are preserved. The location of the circular holes is arbitrary, although they cannot overlap.

Fig. 1 shows a sample calculation of the modal characteristics of the 2-degenerate fundamental mode for a 3-ring structure with $\Lambda = 1.2\mu$m and holes of diameter $d = 1.08\mu$m. The calculated propagation constant is $n_{eff} = 1.29584423675 + 9.825 \times 10^{-9}i$, corresponding to a loss of 0.35 dB/m and an effective area of 1.75 μm^2 at 1550nm, that is of the same order of the one reported in Ref. 1 for a real HF. The confinement loss for small-core HFs as a function of the number and dimension of the holes and of the modal effective area will be presented and discussed.

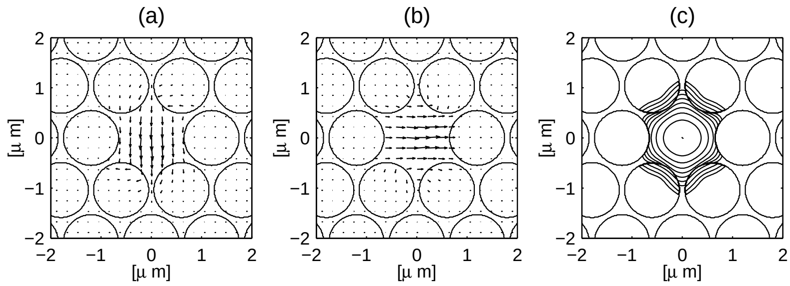

Fig. 1: *Degenerate fundamental mode: (a) transverse electric and (b) magnetic fields; (c) Normalized poynting vector (contours spaced by 2 dB). See text for MOF structure details.*

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Supercontinuum generation in photonic crystal fibers

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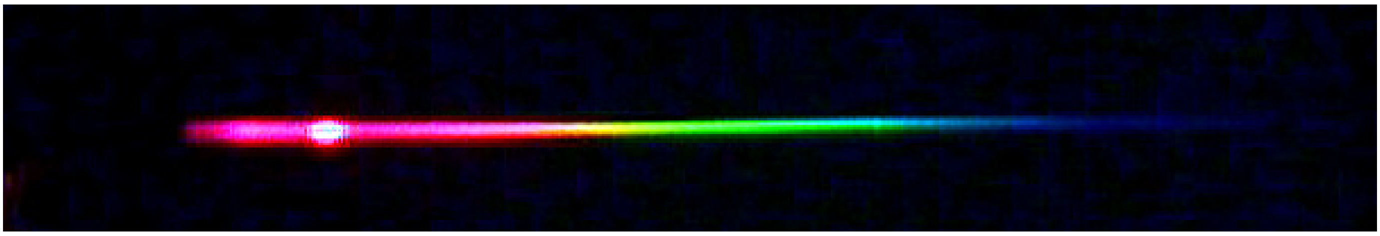
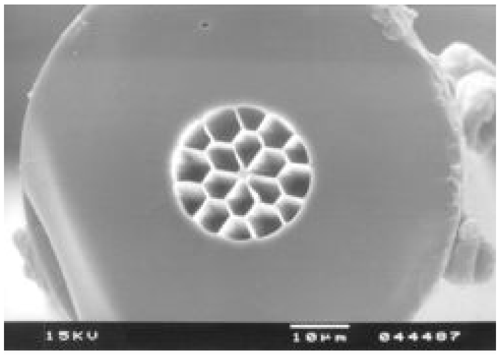
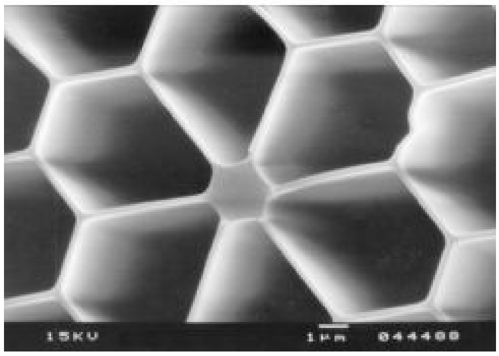


Supercontinuum (SC) generation is a complex nonlinear phenomenon that is characterized by the dramatic spectral broadening of intense light pulses passing through a nonlinear material [1]. It was first observed in 1970[2]. Since then, it has been shown to occur in various nonlinear media and has been extensively used in numerous applications ranging from spectroscopy to ultrashort pulse generation [1]. The spectral slicing of SC laser sources has also been proposed as a means to make a multiwavelength source for wavelength-multiplexed optical telecommunications [3] and, more recently, an ultra-broadband SC spanning more than an octave from the ultraviolet to the infrared has been applied to high precision optical frequency metrology [4].

The development of photonic crystal fibers (PCF) has recently led to the demonstration of white-light SC generation directly from unamplified femtosecond Ti:Sapphire oscillators [5]. PCF are made up of a pure silica core surrounded by an array of microscopic air holes running along their entire length (see the scanning-electron micrographs to the right). The large refractive-index step between silica and air allows light to be concentrated into a very small area, resulting in enhanced nonlinear effects. Moreover, because of the large waveguide contribution to their group-velocity-dispersion, PCF can exhibit very unusual chromatic dispersion characteristics. These two properties are the key for efficient supercontinuum generation.





In contrast to most previous experiments that were relying on femtosecond pump pulses [4,5], we have studied SC generation in PCF with much longer picosecond pump pulses (60 ps). The figure at the top of this page, that shows the spectrum of the light leaving a 10m-long PCF excited with 700 W peak power pulses, demonstrates that SC generation is also possible in those pumping conditions, therefore revealing that ultra-broadband white-light SC generation does not require a complex ultrafast laser.

In our experiments, the spectral broadening has been identified has being due to stimulated Raman scattering and parametric four-wave mixing generation, with a negligible contribution of the self-phase-modulation of the pump pulses [6]. The observation of a strong anti-Stokes Raman component has also revealed the importance of the coupling between stimulated Raman scattering and parametric four-wave-mixing in highly nonlinear photonic crystal fibers, and has also indicated that non-phase-matched processes contribute to the continuum. Additionally, the pump input polarization affects the generated continuum through the influence of polarization modulational instability. To complement our experimental study, a detailed numerical model of SC generation in PCF has also been developed. The numerical results are in good agreement with the experiments. These findings demonstrate the importance of index-guiding photonic crystal fibers for the design of picosecond or nanosecond supercontinuum light sources.

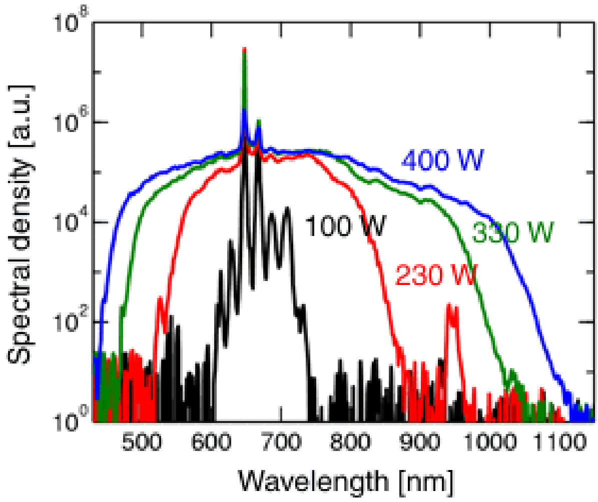


Illustration of the broadening of the spectrum and the formation of the supercontinuum for increasing peak input powers. The PCF used here was 3 m long.

In our talk, we will give a review of past and present supercontinuum experiments and we will describe the different mechanisms and techniques that can be used to generate a supercontinuum spectrum. We will then present our most recent experimental and numerical results.

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Development and applications of ytterbium-doped highly nonlinear holey optical fibres

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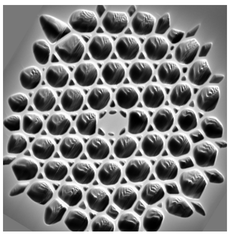
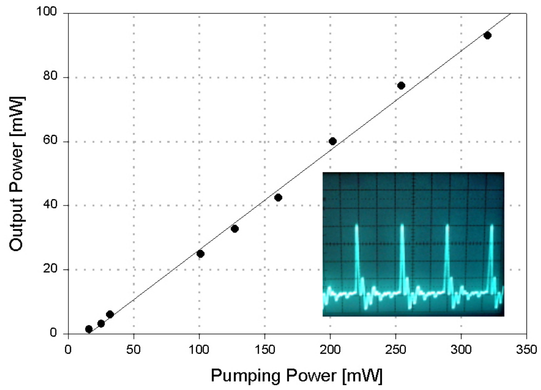
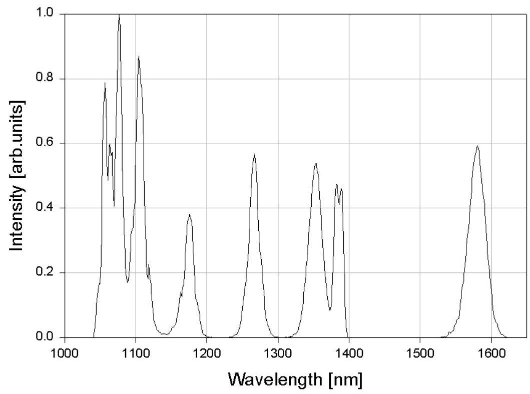
We have fabricated an ytterbium doped holey fibre with an effective area of just 2.5μm^2 at the laser wavelength (1.03μm) as shown in Fig. 1(a). The fibres display huge birefringence at 1.55μm (beat length 0.3mm) owing to the high index contrast between the core and the cladding, the small dimensions, and the elliptical core shape. Using this fibre, we have demonstrated a low threshold and environmentally stable mode-locked laser using frequency feedback technique (see Fig. 1(b)). Furthermore, the fibre exhibits anomalous dispersion at the laser wavelength. Using this feature along with the high nonlinearity, we have also demonstrated broadly and continuously tunable Raman soliton generation by seeding with only pico-joule femtosecond pulses into the fibre. In a single pulse regime, the tuning range covers from 1.06 to 1.33μm, a region that is difficult to access using conventional solid state laser technology. In a multiple pulse regime, we have obtained femtosecond pulses as long as 1.58μm as shown in Fig. 1(c).



(a)





(b) (c)

Fig. 1: *(a) SEM of the ytterbium holey fibre. (b) Output characteristics of the mode-locked ytterbium holey fibre laser. (c) Output spectrum at high pump power.*

POSTERS

Thursday and Friday, October 25 and 26, 2001

Poster-1

Periodic modulation of the refractive index by vortex-lattices

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We demonstrate experimentally the generation of square and hexagonal lattices of optical vortices and reveal their propagation in a saturable nonlinear medium. If the topological charges (TCs) of the vortices are of the same sign the lattice exhibit rotation, while if alternative we observe stable propagation of the structures. In the nonlinear medium (NLM) the lattices induce a periodic modulation of the refractive index. We observed diffraction of a probe beam by the nonlinearity-induced periodic structure of the refractive index.

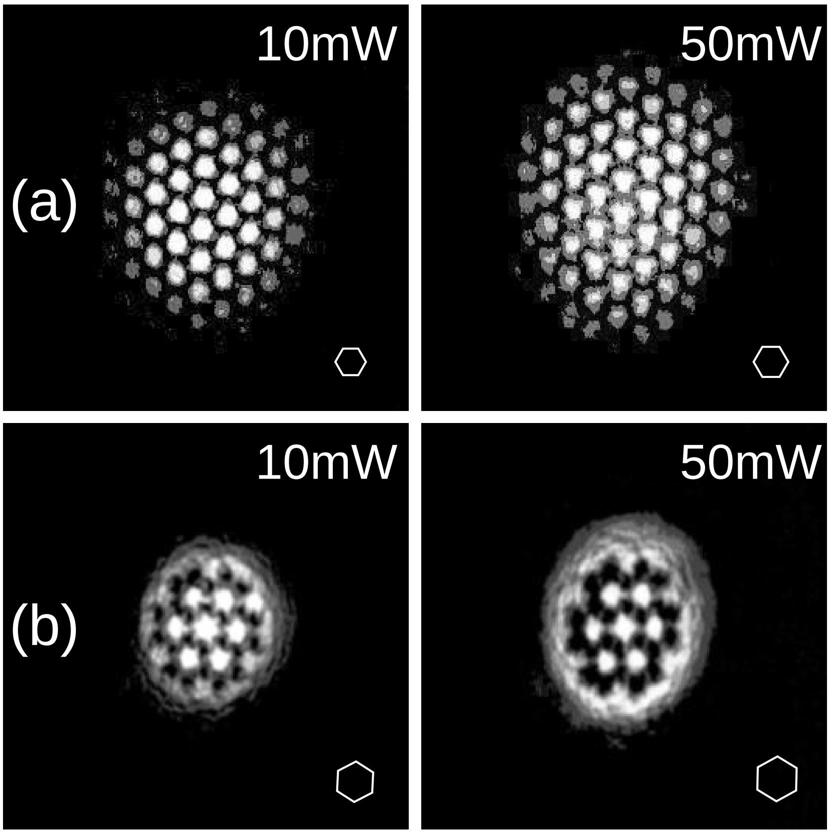

Fig. 1: *Experimental images of the vortex lattices at 10cm propagation in the NLM. (a) - hexagonal lattice with alternative charges for powers 10mW and 50mW. (b) - hexagonal lattice with equal charges for the same powers. The insets in each image represents the size and the orientation of the elementary cell of each lattice.*

In Fig. 1 we show the experimental images for hexagonal honeycomb lattice with equal and opposite TCs and two different powers at the end of the nonlinear medium (ethylene-glycol dyed with DODCI). The images show clearly the rotation of the lattice with opposite TCs and the steady propagation of the other. Due to the self-defocusing the beam spreads out at higher power.

The observed periodic structure of the intensity distribution also induces periodic modulation of the refractive index of the medium. This modulation is sufficient to cause a perpendicularly propagating He-Ne laser beam to diffract. We belive that idea gives a new way for dynamic creation of two-dimensional photonic band-gap structures.

Poster-2

Supercontinuum generation in crystal fibres

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Since the first fabrication of a holey fiber in 1996 [1], many investigations on the remarkable properties of these fibers have been done. Holey fibers are now used in many areas as nonlinear optics, quantum electrodynamics, fiber optics, spectroscopy, biomedical optics, metrology and many others [2]. Photonic-crystal-fibers (PCFs) are holey fibers where the cladding holes are arranged in periodicity. Due to that periodicity a photonic band-gap in the transmission spectra perpendicularly to the waveguide direction is formed. The photonic band-gap effect gives rise to an engineerable waveguide contribution of the group-velocity-dispersion and very unusual chromatic dispersion characteristics can be achieved using PCFs. Another important property of PCFs is the strong confinement of the light around the fiber core, wich gives rise to strong nonlinear effects. These two features lead to the possibility of effective generation of supercontinuum light in PCFs

We investigated the dispersion properties of PCFs wich were then used to model the propagation of ps and fs pulses by numerical integration of generalized coupled nonlinear Shrödinger equations. As it was recently shown experimentaly and numerically by Coen et al. [3], our simulations show that PCFs are a very promising tool for supercontinumm generation.

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Poster-3

Crystal Fibre A/S

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Crystal Fibre A/S is strongly committed to innovation, dedicating large resources to research and development.

We design, manufacture and market photonic crystal fibers. Photonic crystal fibers are a new range of optical fibers characterize by a micro-scale structure extending along the length of the fibers. Advantages of the technology include pure silica core fibers and numerous novel properties. The technology provides a large design flexibility, which can be utilized for a large range of specialty fibers.

Crystal Fibre is committed to development of the fiber technology, working in close collaboration with our customers on supporting their applications

History: Crystal Fibre A/S was founded as in late 1999. The company is based on the cofounders' several years of research within photonic crystal fibers extending back to 1996.

Ownership: Crystal Fibre A/S is established as a wholly owned company by NKT Holding A/S. Crystal Fibre A/S is established on the basis of know-how and patent applications held by a number of research scientists at the Center for Communications, Optics and Materials (COM) at the Technical University of Denmark (DTU).

Poster-4

Theoretical analysis of finite-height planar photonic crystal waveguides

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Components based on planar photonic crystals are interesting for integrated optics because light can be manipulated and confined in a spatially small region. It has for example been suggested that light can be guided efficiently around a 90 degree sharp bend [1].

General guidelines will be given for the design of finite-height planar photonic crystal waveguides that support leakage-free guidance of light. The guidelines are obtained by comparing calculated dispersion relations for infinite-height (or two-dimensional) photonic crystal waveguides with dispersion relations for the media above and below the corresponding finite-height photonic crystal waveguide [2].

The guidelines will be supplemented with calculated dispersion relations and field profiles of guided modes in finite-height planar photonic crystal waveguides.

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Poster-5

Engineering and excitation of solitons in two-period QPM

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We report on a scheme which might make it *practically* possible to engineer the effective competing nonlinearities that on average govern the light propagation in quasi-phase-matching (QPM) gratings.

In standard one-period QPM, the grating period normally must be very short in order to compensate the large intrinsic phase-mismatch. Superimposing a second period, two-period QPM, introduces an extra degree of freedom in the system. The second period can be chosen without regard to the intrinsic phase-mismatch. Thus the engineering of spatial solitons based on competing nonlinearities is made practically possible.

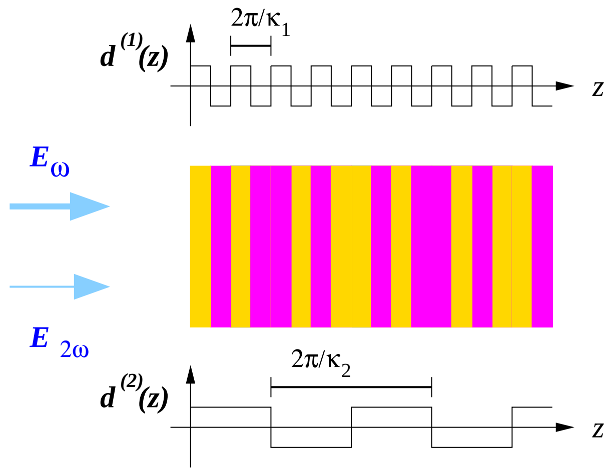

Fig. 1: *Two-period QPM grating.*

For the induced averaged nonlinearities addressed here to be of potential practical importance, they have to impact the observable soliton properties, including their excitation conditions. We found that the QPM engineered averaged cubic nonlinearities, induced in feasible two-period samples, enhances the peak-efficiency and mismatch-bandwidth of the soliton excitation process with non-soliton single frequency pump light.

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