Observation of polychromatic gap solitons

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Abstract: We study theoretically and observe experimentally *polychromatic gap solitons* generated by supercontinuum light in an array of optical waveguides. The solitons are formed through a sharp transition from diffraction-induced broadening and color separation to the simultaneous spatio-spectral localization of supercontinuum light inside the photonic bandgap with the formation of the characteristic staggered phase structure for all colors.

OCIS codes: (190.4420) Nonlinear optics, transverse effects in; (190.5530) Nonlinear optics: Pulse propagation and solitons; (190.5940) Self-action effects.

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#92071 - $15.00 USD Received 24 Jan 2008; revised 4 Apr 2008; accepted 10 Apr 2008; published 14 Apr 2008

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1. Introduction

Periodic photonic structures allow to control the fundamental aspects of wave propagation opening up many possibilities for all-optical tunability of spatial beam propagation in nonlinear media. Interplay between nonlinearity and periodicity gives rise to nonlinear localization in the soliton regime, allowing for the increased resolution in beam steering. Spatial discrete and gap solitons [1, 2, 3, 4] in periodic structures have been a subject of an active study in the recent years [5, 6, 7, 8]. The physics of spatial soliton formation in photonic structures is governed by the creation of a self-induced defect on top of a periodic refractive index modulation. Such defect acts as an effective waveguide which can confine light inside the photonic bandgaps in periodic structures. The presence of bandgaps strongly modifies the wave spectrum and affects the beam diffraction, allowing for existence of solitons with the staggered phase profile in materials with defocusing nonlinearity [2, 9, 10, 11, 12].

So far, spatial gap solitons were generated by monochromatic sources [9, 13, 14, 11, 12]. However, in many practical cases such as ultra-broad bandwidth optical communications and propagation of ultra-short (sub-10 fs) pulses, the bandwidth of the optical signals can span over a wide frequency range. Since the Bragg reflection is a resonant process depending on the wavelength, it is important to understand if localization of broadband radiation through the Bragg confinement can be practically realized. Recent theoretical studies [15, 16] revealed that broadband radiation can be localized in the form of polychromatic spatial gap solitons. In this Letter, we present the first experimental observation of *polychromatic gap solitons* excited by a supercontinuum light source with a spectrum spanning from blue to infrared. We show that the soliton formation occurs through a sharp self-trapping above specific input power, when all colors become localized in the spatial domain. This transition is associated with the simultaneous development of specific phase structure for each of the frequency components, and the

#92071 - $15.00 USD Received 24 Jan 2008; revised 4 Apr 2008; accepted 10 Apr 2008; published 14 Apr 2008

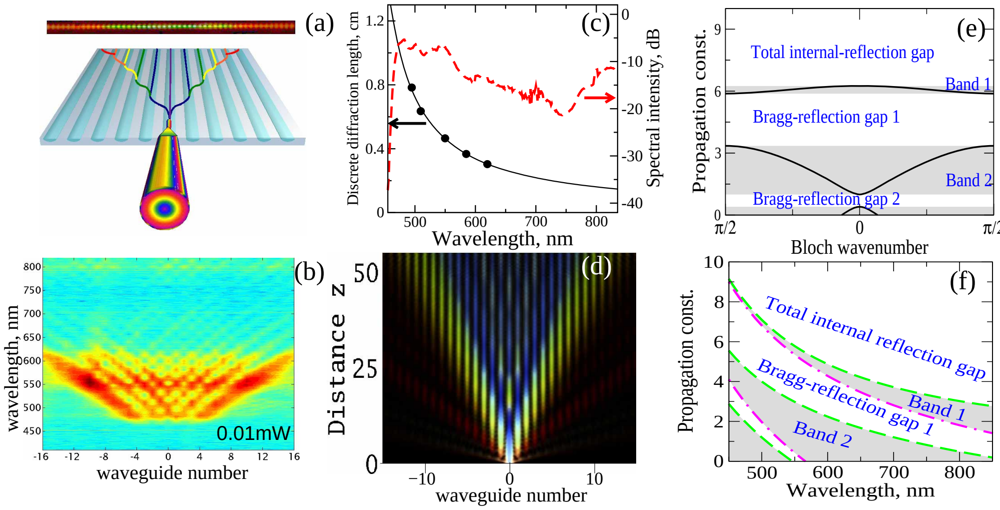

Fig. 1. (a) Schematic of coupling of the supercontinuum to an array of optical waveguides, where different spectral components are redistributed in different waveguides. (b) Measured spectrally resolved output (log scale) from polychromatic discrete diffraction at low average power. (c) Supercontinuum spectrum (red) and measured dispersion of the waveguide coupling length (black). (d) Numerical simulation of linear polychromatic propagation inside the array and spatial separation of colors. (e) Bloch-wave dispersion at 530 nm wavelength. (f) Dependence of photonic bands on wavelength.

shift of the wave spectra inside the photonic bandgap.

2. Characterization of waveguide arrays

We consider the propagation of polychromatic beams through an array of nonlinear optical waveguides [Fig. 1(a)]. In experiments, broadband multi-color beams can be readily generated through supercontinuum generation in photonic-crystal fibers [17, 18]. We generate supercontinuum light of ultra-broad spectrum [Fig. 1(c, red)] by launching 140 fs pulses (800 nm, 6 nJ) in a photonic-crystal fiber with a zero dispersion wavelength at 740 nm. The supercontinuum beam exiting the fiber is attenuated by neutral-density filters to control its total power and refocused into a single channel of a waveguide array (period 10 μm) [Fig. 1(a)]. The array is fabricated by Titanium indiffusion in a X-cut, 55 mm long mono-crystal Lithium Niobate wafer. Due to the strong coupling between neighboring waveguides, at low powers (linear regime) each spectral component exhibits typical discrete diffraction where the light is concentrated into the wings of the beam rather than in its center. Typical polychromatic diffraction pattern is shown at the top of Fig. 1(a), and the corresponding spectrally resolved intensity distribution in each output channel (measured by a spectrometer integrating over each waveguide) is shown in Fig. 1(b). The beam spreading is characterized by the discrete diffraction length, which defines the characteristic distance where the diffraction pattern at the specific wavelength is expanded by two extra waveguides. In our sample the discrete diffraction length varies from 1 cm, for blue (480 nm), to less than 0.2 cm, for red (800 nm) spectral components [Fig. 1(c, black curve)]. These values correspond to propagation between 5.5 and 27.5 discrete diffraction lengths for the blue and red spectral components, respectively. Compared to our earlier experiments [19, 20], this new sample was designed to feature much stronger diffraction, which is essential for the studies of spatial soliton formation [7, 21]. As a result, the individual spectral components become redistributed among different channels of the array. We observe that the red components dominate in the beam wings, while the blue components are dominant in the

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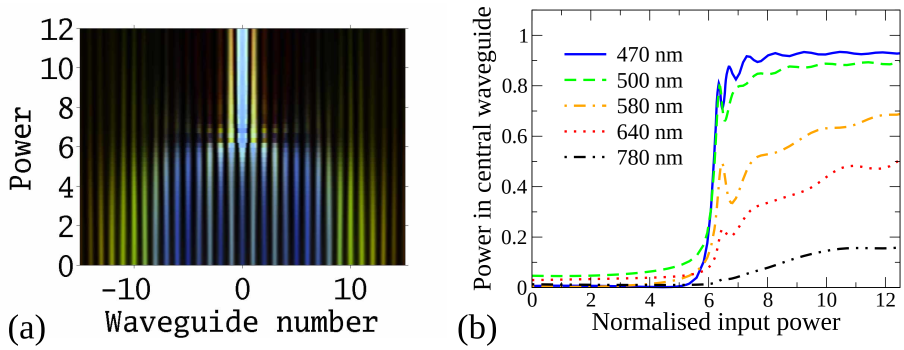

Fig. 2. Numerically calculated dependence of the output beam characteristics on the input supercontinuum power: (a) transformation of the output beam profile, and (b) the fraction of output power remaining at the central waveguide for different spectral components.

central region, effect somewhat analogous to the superprism phenomena in photonic crystals.

The obtained linear dispersion properties allow us to model the spectral field evolution inside the array. According to planar structure geometry, the beam is trapped in the vertical (y) direction and we use the standard reduction procedure [7] assuming that the field structure in y follows the profile of fundamental guided modes. Then, we obtain a set of equations for the spatial beam envelopes $A_m(x,z)$ of different frequency components at vacuum wavelengths λ_m, $i\partial A_m/\partial z + \lambda_m(4\pi n_0)^{-1}\partial^2 A_m/\partial x^2 + 2\pi\lambda_m{}^{-1}\Delta n(x;\lambda_m)A_m = 0$, where x and z are the transverse and longitudinal coordinates, respectively, and $n_0 = 2.3$ is the average refractive index. The dominant dispersion contribution comes from the geometric dispersion, such that the value of n_0 can be taken as constant for the whole spectral range, while the effective refractive index modulation $\Delta n(x;\lambda_m)$ exhibits significant dispersion. For our waveguide array, away from the boundaries, the modulation can be approximately described as $\Delta n(x;\lambda) = \Delta n_{\max}(\lambda)\cos^2(\pi x/d)$, where the wavelength dependence of the effective modulation depth $\Delta n_{\max}(\lambda)$ is calculated by matching the experimentally measured waveguide coupling. Numerical simulation of supercontinuum light diffraction inside the waveguide array is shown in Fig. 1(d).

3. Excitation dynamics of polychromatic solitons

The important next step is to study the possibility to suppress the diffraction-induced broadening and separation of spectral components through nonlinear beam self-action. At high laser powers, the spectral components interact incoherently with each other (no new frequency components are generated) due to the intensity-dependent change of the optical refractive index [22] through the photovoltaic effect. A characteristic property of the photovoltaic nonlinearity in Lithium Niobate is that an increase of the beam intensity leads to a decrease of the material refractive index [23]. Although the negative nonlinear response would result in self-defocusing and accelerated beam broadening in bulk media, beams can exhibit self-trapping in the periodic media due to the presence of photonic bandgaps in the linear wave spectrum. At each wavelength, the dependence of longitudinal propagation constant (along z) on the transverse Bloch wavenumber (along x) has a universal character in one-dimensional lattices [24], where the spectrum consists of non-overlapping bands separated by photonic bandgaps as shown in Fig. 1(e) for a wavelength of 530 nm. The size of the photonic gap determines the properties of monochromatic gap solitons as well the required excitation power [12]. The position and the gap width, however, are strongly sensitive to the wavelength of the light [Fig. 1(f)]. It is therefore an intriguing problem of how the self-trapping of polychromatic beams would occur, given such strong dependence of the band-gap spectrum on wavelength.

We model the nonlinear propagation and interaction of all spectral components by includ-

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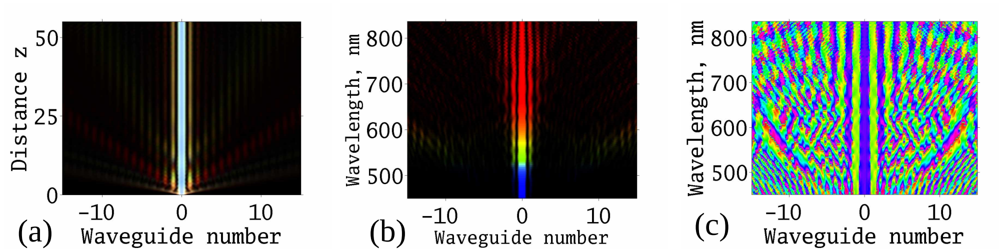

Fig. 3. Numerically calculated beam evolution for the normalized power $P_0 \simeq 12$. Shown are (a) the beam propagation dynamics inside the array; (b) spectrally resolved output intensity profiles; and (c) output phase profiles of individual spectral components.

ing a nonlinear spectral response into the refractive index modulation [25], $\Delta n_{\rm nl}(x,z;\lambda) = \gamma M^{-1} \sum_{j=1}^{M} \sigma(\lambda_j)|A_j|^2$. We choose a larger number of frequency components ($M = 100$) in order to accurately model the supercontinuum power spectrum and approximate the photosensitivity dependence by a Gaussian function [16] $\sigma(\lambda) = \exp[-\log(2)(\lambda - \lambda_b)^2/\lambda_w^2]$ with $\lambda > \lambda_b = 400\,$nm and $\lambda_w = 150\,$nm. Our numerical simulations show that the input beam experiences self-trapping above a critical power level, see Fig. 2. There is a sharp transition between the regimes of diffraction and soliton formation, associated with collective localization of spectral components. Such transition occurs because the length of waveguide array is several times larger than the diffraction lengths at each of the spectral components. This effect differs drastically from the beam reshaping reported previously [20] under the conditions when diffraction of blue components is very weak, such that they remained localized at the output even in the linear regime, and the power increase provided a gradual onset of localization only at longer wavelengths. The new experimental samples were also designed to have sufficiently wide bandgap avoiding the cross-over to defocusing which could occur if the band-gap was narrower [15]. Accordingly, all components can experience collective self-trapping, such that the soliton preserves its input 'white' color [see Fig. 3(a)]. Note that the red and infra-red components are also trapped [see Fig. 3(b)], although their localized profiles extend over several waveguides due to stronger diffraction and effectively weaker nonlinearly-induced potential which is inversely proportional to the wavelength. Therefore, for localized modes at longer wavelengths, the power fraction at the central waveguide can remain relatively small, which explains why the self-trapping transition for red and infra-red components is less visible in Fig. 2(b).

A characteristic feature of gap solitons localized within the Bragg-reflection gap is the appearance of staggered phase structure. In the case of supercontinuum gap solitons, the phases of different wavelength components are not synchronized together, however each component has a well-defined phase front due to the strong spatial coherence of supercontinuum radiation. We plot the phase profiles in Fig. 3(c), which show the simultaneous appearance of the staggered phase structure for all individual spectral components. Hence, such localization represents a uniquely different physical picture compared to the theoretically studied white-light solitons in lattices supported by a focusing nonlinearity [26] where the defined phase relation is not required for soliton formation.

4. Experimental observation of polychromatic gap solitons

In agreement with the theoretical predictions, we observe strong spatio-spectral localization of the supercontinuum light as its input power is increased [Figs. 4(a-c)]. In a narrow range of input powers ($150 - 250\,\mu$W) the beam profile narrows from over 50 waveguides [Fig. 4(a)] down to three central waveguides [Fig. 4(b)]. This transition, indicating the formation of a polychromatic soliton, happens over a range of $100\,\mu$W only and appears extremely sharp comparing with the fact that further localization down to a single waveguide of the array requires addi-

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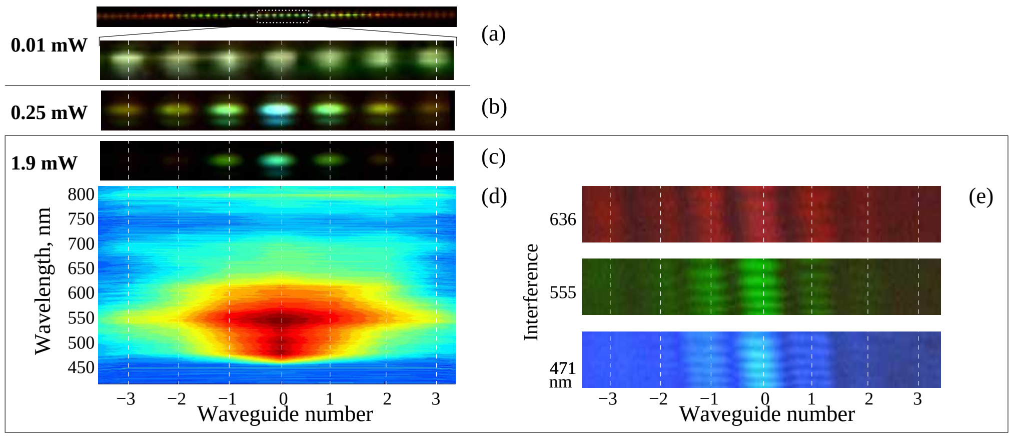

Fig. 4. Experimental observation of polychromatic gap soliton: (a-c) Real-color CCD camera images of the output beam intensity profile: (a) Diffraction profile at low power; (b,c) Nonlinear localization and formation of polychromatic gap soliton with increasing supercontinuum power. (d) Spectrally resolved measurements of the profile (c). (e) Interferograms of the output beam profile (c) with a tilted reference supercontinuum beam, imaged at three different wavelengths as indicated by labels.

tional increase of 1.5 mW (15 times larger) [Fig. 4(c)]. The important characteristic of this localization is the fact that it combines all wavelength components (from blue to red) of the supercontinuum spectrum [Fig. 4(d)]. Localization around 700-750 nm wavelengths is not visible due to the lower spectral intensity of these components in the input supercontinuum spectrum [see Fig. 1(c)], whereas the formation of localized profile over 6 central waveguides is observed at 800nm wavelength.

Taking advantage of the high spatial coherence of the supercontinuum light, we perform interferometric measurement of the localized output profile. We place a beam splitter before the waveguide array to produce a reference beam, which is then sent through a variable delay-line, implemented in a dispersion compensated interferometer, including an additional 5 cm long bulk $LiNbO_3$ crystal to match the pulse dispersion inside the $LiNbO_3$ waveguides for the probe beam. In this way, interferometric measurements are possible for ultra-wide spectral range. The reference beam is slightly tilted in the vertical plane in comparison to the probe beam, thus producing interference fringes. The interference patterns have different periods depending on wavelength, and therefore had to be imaged separately using a tunable linear filter (LVF, Ocean Optics) mounted in front of the CCD camera. The recorded images presented in Fig. 4(e) show that the interference fringes between neighbouring waveguides are shifted by half a period, hence the probe beam phase changes by π between them. Most remarkably, such staggered phase structure appears simultaneously in an ultra-broad spectral range from blue (470 nm) to red (above 630 nm), providing direct evidence that the localized beam is indeed a polychromatic gap soliton.

5. Conclusions

In conclusion, we have presented the first observation of polychromatic gap solitons in periodic photonic structures with defocusing nonlinearity, generated by self-trapping of supercontinuum radiation in the photonic bandgaps. The development of the well-defined staggered phase profile in different spectral components demonstrates an opportunity for nontrivial phase control of supercontinuum radiation.

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