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Periodic refocusing in microstructured fiber for efficient quasi-phase matched optical nonlinearity

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Abstract

We demonstrate periodic light refocusing within a solid-core photonic bandgap microstructured fiber design. This technique offers enhanced efficiency in quasi-phase matched optical non-linear applications. Spatial periods varying from 17μm – 43μm are possible.

1 Summary

Microstructured fiber (MSF), such as photonic crystal fiber (PCF) [1], Bragg fiber [2] and zoned MSF [3], offers numerous design possibilities compared to conventional single-mode fiber (SMF). Recently, new MSF designs have also emerged with enhanced optical nonlinear properties. This has been achieved by a combination of novel materials (e.g. bismuth glasses), and very small mode sizes [4]. In addition, the use of quasi-phase matching (QPM) techniques has also been developed to enhance nonlinear interaction efficiencies, e.g. via periodic-poling [5]. Recent work by Pfeifer *et al.* [6], has also demonstrated the feasibility of QPM in hollow-core fiber, by means of two-mode beating effects. In this paper, we present a novel MSF design which exploits the inherent fiber geometry to enhance the efficiency of optical nonlinear effects by QPM. This is achieved by careful phase-matching of all modes in a multimoded waveguide structure, so that the modes become spatially and periodically "mode-locked". In previous work, we exploited a similar MSF geometry to demonstrate photonic bandgap light confinement in hollow-core radially-chirped Bragg fiber (RCBF), featuring an aperiodic geometry [7]. We continue to exploit the photonic bandgap effect to confine the light within our MSF design, so highlighting the flexibility of our approach in possible choices of optical nonlinear media. In the RCBF case, the zoned MSF can also be regarded as the longitudinal embodiment of a binary Fresnel zone plate [8], such that light is guided by periodic refocusing back within the fiber structure. Alternatively, the periodic refocusing of the light within the fiber core is arguably analogous to the Talbot self-imaging effect, exploited within multi-mode interference (MMI) couplers. However, rather than employing an essentially periodic grating as is required for the 1D case, the cylindrical geometry of a fiber requires aperiodic gratings [9] to achieve the same self-imaging effect.

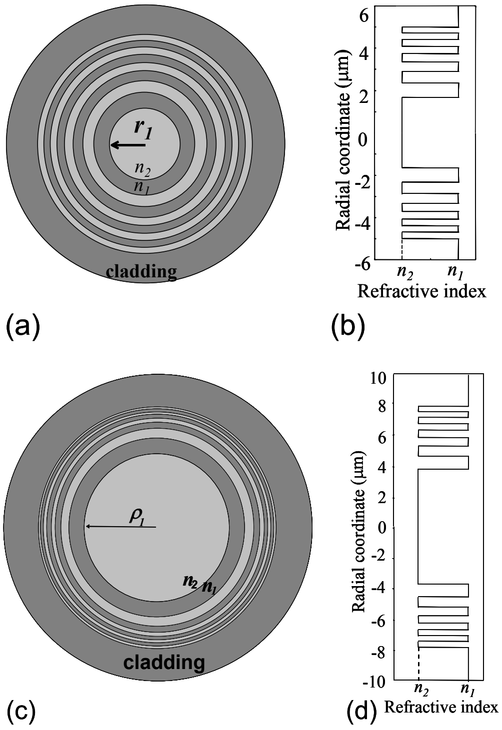

Fig.1: Schematic diagrams of solid-core RCBF and refractive index profiles with: (a) & (b) r_1=1.67μm; (c) & (d) ρ_1=3.92μm

We have adopted a simple Fresnel zoning geometry to achieve the refocusing effect, although the zeroes of a Bessel function could also be exploited; this being the subject of future research. Figure 1 shows schematic cross-sections of the two solid-core RCBF waveguide geometries that we have simulated. For a Fresnel zone configuration, the general expression for the radius r_m of the m^{th} zone is given by the equation $r_m = \sqrt{m} r_1$, where r_1 is the central zone radius. This simple square-root relationship presupposes closely similar refractive indices for the different zones, such that overall optical path lengths are in the same proportion as geometric path lengths. In the geometry of fig. 1(a)&(b), the center (geometric) radius is given as $r_1 = 1.67\mu\text{m}$, with center refractive index given by n_2=2.25, whilst the subsequent index is n_1=2.35, and there are 9 zones. Fig. 1(c)&(d) shows a MSF geometry with a larger central zone radius, ρ_1=3.92μm. However, rather than following the conventional zone radii of the Fresnel formula, we have maintained the same zone radii increments of the previous geometry in a manner similar to that used in [7], such that the subsequent zone radii are given by $\rho_m=\rho_1+(r_m-r_1)$, where ρ_1=3.92μm, r_1=1.67μm, and r_m follows from the square-root Fresnel formula. We have used a fully vectorial 3D finite-difference time-domain (FDTD) package, *Poynting for Optics*, to simulate electric field evolution in our MSF designs.

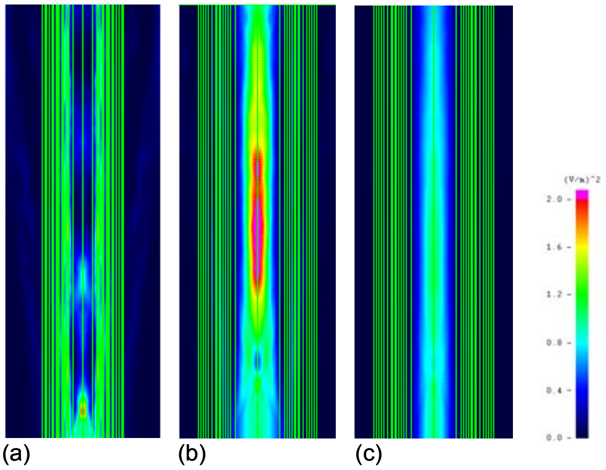

Fig. 2. Modal evolution along 55μm lengths of solid-core RCBF fiber with central zone radius: (a) r_1=1.67μm, input light source D_s=9μm, Λ=17μm, (b) ρ_1=3.92μm, input light source D_s=9μm, Λ=30μm, (c) ρ_1=3.92μm, input light source D_s=6μm, Λ=43μm.

Fig.2(a) shows the evolution of a linearly-polarised D_s= 9μm width Gaussian input mode source ($\lambda = 1.55\mu\text{m}$) along a 55μm-length of the fiber shown in fig.1(a). The periodic refocusing of the light is a marked effect, with a spatial period of Λ=17μm within the low refractive index core of the fiber. This is the key result of our paper. The vertical (green) lines indicate the zone boundaries. In the FDTD simulation, time steps were dt=133as, whilst a minimum spatial resolution of dx=dy=100nm for transverse dimensions, and dz=50nm (along the fiber axis) were employed. Fig. 2(b) and 2(c) show how the spatial period Λ can be tuned by varying both fiber geometry and also the Gaussian diameter D_s of the illuminating light. In this case, the period Λ can be increased by either increasing the radius of the central zone, e.g. Λ can be increased to Λ=30μm for the central zone radius of ρ_1=3.92μm. Furthermore, reducing the diameter of the source light to D_s=6μm also increases the spatial period further to Λ=43μm. In these two latter cases, the FDTD simulation parameters were increased slightly to dt=144as and dx=dy=131nm, with dz=50nm, in order to accommodate the larger fiber structure within the computing memory resources. In summary, we have shown how fiber geometry can be exploited to further enhance within-fiber optical non-linearities with QPM techniques via periodic Talbot-like imaging. Optimisation of the QPM spatial periodicity Λ is made possible by appropriate MSF geometric design, whilst dynamic tuning of Λ is also available by varying the diameter D_s of the illuminating light source.

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