Supercontinuum generation in web-like microstructure optical fiber

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A novel web-like microstructure optical fiber (MOF) is fabricated which serves as a bundle of suspended submicron-thickness membranes as planar waveguides and their Y-type connection nodes as the secondary cores. The polarization dependent visible continuum coverage from 350 to 1 000 nm is generated from a 20-cm-long membrane of 0.55-μm-thickness pumped by 200-fs laser at 800 nm. We also obtain narrowband signal of blue dispersive wave around 410 nm with the up-conversion efficiency routinely beyond 20% in the Y-type secondary core in another smaller web-like MOF.

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Supercontinuum generation (SCG) in microstructured optical fibres (MOFs) has been a subject of intense research in the past decade[1−3]. Small core silica MOFs, possessing enhanced modal confinement and group velocity dispersion (GVD) tailoring, make them excellent media for nonlinear applications[4]. SCG has been observed from a variety of special-core-shape MOFs pumped in their different dispersion regime. For instance, MOFs can be designed with suspended membrane[5,6] and core[7,8]. Such fibres offer ease of fabrication arising from their much simpler geometry, and demonstrate efficient SCG as well as strong polarization controllability. Also, such fibres show great potential applications as evanescent wave sensor[9,10], the interaction can be greatly enhanced between the measured matter in large air channel and the evanescent wave. However, previous works never reported the integrated waveguides of membranes (planar waveguide) and the secondary cores, not to mention the nonlinear spectral broadening in such MOF. Here, we fabricated firstly, as to our knowledge, a novel web-like MOF, which served as a bundle of suspended submicron-thickness membranes as planar waveguides and their Y-type connection nodes as the secondary cores[11]. The polarization dependent visible continuum has been observed from a 20-cm-long membrane with 0.55-μm-thickness pumped using 200-fs pulse at 800-nm wavelength and achieves a broad range from 350 to 1 000 nm for the TM mode excitation. We further obtained the narrow blue dispersive wave generation around 410 nm in the Y-type secondary core with up-conversion efficiency beyond 20%, enabling multimilliwatt blue output.

The fibre is manufactured using the stack-and-draw method by the Yangtze Optical Fibre and Cable Company Ltd. Our initial purpose is to fabricate a multifunctional integrated MOF which can supply different types of waveguides in one fibre. A scanning electron micrograph (SEM) of the fibre is shown in Fig. 1(a). In the center of the fibre cross section is a large regular hexagon air hole surrounded by six annular air holes. All the inner six narrow web-like glass membranes are ∼20-μm width, their measured thicknesses are 0.55, 0.53, 0.5, 0.47, 0.45, and 0.34 μm, respectively. These membranes, in turn, provide different dispersion curve for nonlinear SCG. Figure 1(b) shows a part of membrane and the Y-type secondary core. The membrane has quite uniform thickness, while the inscribed circle of the secondary core has a diameter of ∼1.2 μm. The MOF has an out-diameter of 170 μm. The nonlinear spectrum broaden is studied by pumping the fiber with a Ti:Sapphire laser (Mira900 Coherent) which can deliver 200-fs linearly polarized pulses centered at 800 nm. A 40× micro-objective lens with a NA of 0.65 is used to couple the pump light into any waveguides of interest using a method as mentioned in Ref. [11]. The fiber used in experiment is 20-cm-long length. A half-wave plate is used to vary the incident pulse polarization. The output spectrum is recorded after collimating the output beam by an optical spectrum analyzer (YOKOGAWA-AQ6370B, 350–1 200 and 600–1 700 nm).

The GVD is calculated using the finite element module (Comsol Multiphysics, version 3.5a) in our work. The dispersion curves of TE_{00} and TM_{00} modes in the 0.55-μm-thickness membrane are shown in Fig. 2(a). For the TE_{00} mode, the dispersion is normal over the entire concerned wavelengths, while for the TM_{00} mode, the dispersion is anomalous in wavelength range from

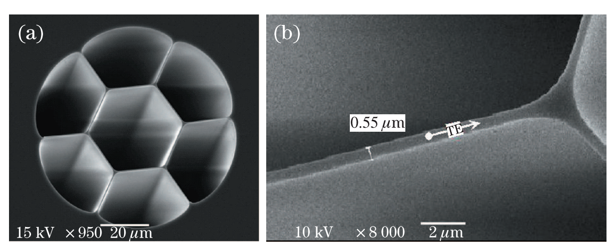

Fig. 1. SEM of (a) nanoweb fibre and (b) 0.55-μm–thickness membrane and the Y-type secondary core.

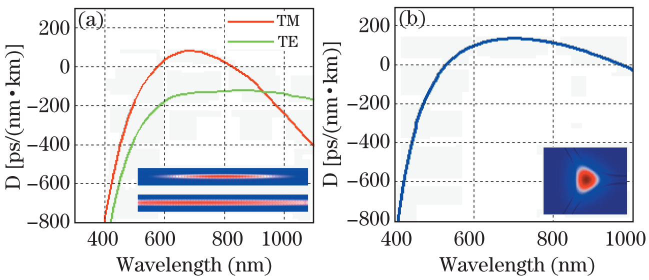

Fig. 2. Dispersion curves of (a) the TM_{00} and TE_{00} modes in the 0.55-μm-thickness membrane and (b) the Y-type secondary core. The insets are the corresponding mode patterns.

~570 to 830 nm. The dispersion curve of the Y-type secondary core is shown in Fig. 2(b), its anomalous dispersion ranges from ~660 to 1 550 nm.

As shown in Fig. 1, The modes in nanoweb fibers can be divided into two groups according to their polarization properties, the TE modes in the width direction and TM modes along the thickness direction.

In Fig. 3, θ is the angle between the polarization direction of the input pulse and the width direction of the membrane. At θ=0°, only TE modes are excited in the normal dispersion regime, hence the spectral broadening of the initial laser pulse, mainly caused by the self-phase modulation, is narrow and symmetrical. The spectra recorded between 0°–90° might result from a combined contribution of P_{TE} and P_{TM}. On the other hand, only TM modes at θ=90° are excited with anomalous dispersion at the pump wavelength, the optical soliton red-shift and the blue dispersive wave are observed, which leads to the generation of a broad supercontinuum (SC) range from ~350 to ~1 000 nm. The incident power P_{i} can be split into two parts according to θ, $P_{\mathrm{TE}}=P_{\mathrm{i}}\cos^2\theta$ for TE mode excitation and $P_{\mathrm{TM}}=P_{\mathrm{i}}\sin^2\theta$ for TM mode excitation. So, the spectra recorded between 0°–30° is mainly generated by TE mode, while the spectra recorded between 40°–90° is mainly generated by TM mode. The recorded power at fiber output end are 100 mW at θ=0° and 61 mW at θ=90°, respectively. We can find that the corresponding excited mode patterns contain not only the fundamental mode (θ=90°), also higher order modes (θ=0°–40°) as shown in Fig. 3. Therefore, the spectral broadening is a complicated process involving many modes, which is proved by slightly changing the pumping condition and measuring the far field patterns in our experiment. It should be noted here the SCG is quite weak in the other thinner membranes, because the 800-nm pump light is located in their normal dispersion region, greatly reducing the soliton red-shift. So, it is appreciated for SCG through appropriate design the thickness of membranes or selection of the pumping wavelength of laser source to their anomalous dispersion region.

Figure 4 shows the recorded spectrum generated from the Y-type secondary core. A distinct property is that the generated blue dispersive wave is quite narrow and effective. It centers at ~410 nm with full width at half maximum (FWHM) less than 10 nm. The total output power of SC is measured to be 70 mW and the power ratio of the ~410 nm surpasses 20% by filtering out the light above 532 nm via a dichroic mirror (DM, HR>532 nm and HT<532 nm). It is tempting to attribute the observed ~410 nm narrowband emission to the blue-shifted pulse trapped by the first and the strongest fundamental soliton undergoing the largest red-shift around 1 600 nm. Also, the up-conversion efficiency is expected to be further enhanced by adding appropriate DM pairs to form laser cavity.

In conclusion, we fabricate a web-like MOF serving as a bundle with suspended membranes and Y-type of secondary cores. The polarization dependent visible SC is obtained in the 0.55-μm-thickness membrane with a length of 20 cm and the generated spectrum coverage from ~350 to 1 000 nm for the TM mode excitation. As we pump the Y-type secondary core, we obtain a narrow and efficient blue dispersive wave centered at 410 nm with FWHM less than 10 nm, the corresponding up-conversion efficiency surpasses 20%. Except the SCG in this work, this type of MOF can also be applied in evanescent field sensing of air or chemical components in the large cladding air holes.

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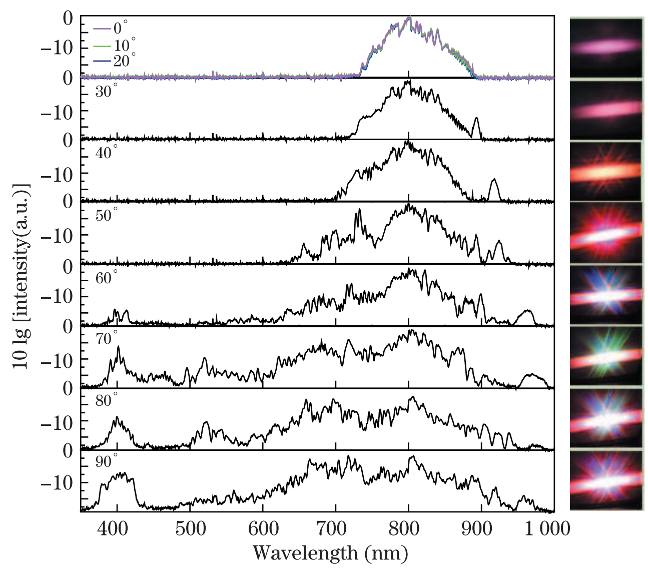

Fig. 3. Recorded spectra in the 0.55-μm–thickness membrane for θ=0°–90° excitation in steps of 10°.

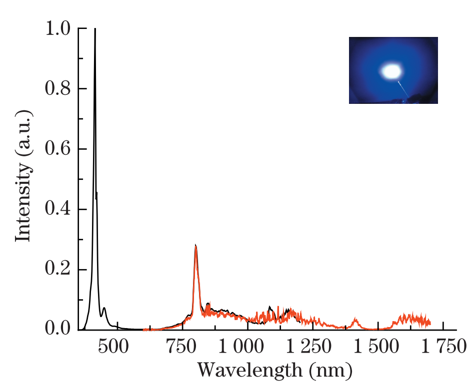

Fig. 4. Recorded spectrum of Y-type secondary core.

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