Optical and Acoustical Methods in Science and Technology

Multicore Optical Fibres for an External Talbot Cavity

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In the paper the application of multicore optical fibres in phased-locked high power lasers is presented. The manufacturing and properties of multicore active optical fibres were presented. The thermally stable aluminosilicate glass doped with Nd^{3+} (0.5 mol%) ions were melted and used as cores in manufactured multicore optical fibres. Two configurations of double clad multicore optical fibres with the circular array containing 15 and 30 Nd^{3+} doped cores on ring inside a large pump clad were realized. Absorption and luminescence spectra of obtained glasses and fibres were presented. An external plane mirror located at certain distance of the array forms the basic Talbot cavity. The possibilities of mode selection and phase-locking by using Talbot resonator applied to fabricated multicore fibres were investigated.

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1. Introduction

Thanks to their favourable properties like: high gain, low excitation threshold, good heat dissipation, high conversion efficiency, and high beam quality, fibre lasers are very attractive sources for many applications and have been intensively developed. Fibre lasers based on multicore optical fibres present a novel approach in designing short length high power fibre laser. Multicore optical fibre (MCF) makes it possible to reduce the fibre length necessary to absorb the pump radiation and increase the maximum laser output power [1]. The major disadvantage of such construction of emitter array is low beam brightness [2, 3]. It is caused by lack of coherence between radiation from individual cores. Mutual coherent emitters provide high output power with high brightness laser beam. When the emitters operate in in-phase coherent mode, the far field produces high intense central lobe with symmetric side lobes. The divergence of the central lobe is then narrowed in proportion to the element number N of the coherent array. Recently have been shown a few phase-locking methods [4]. Active phase correction was used for the individual fibre laser. However, these systems were complicated and unstable because of vibration, changing temperature, etc. [4, 5]. One possibility to phase-lock of an array of emitters is use of the Talbot resonator.

2. Talbot resonator

The principle of Talbot effect is that the field distribution self-reproduces completely after certain distance. It is called Talbot distance Z_T:

$$Z_\mathrm{T} = \frac{2d^2}{\lambda}, \tag{1}$$

where d — period distance, λ — wavelength.

Figure 1 presents a basic idea of Talbot resonator. In this construction the emitters array in fibre are arranged in a periodic structure. Doped cores are placed on ring inside a large pump clad. If radiation from all microcores is mutual coherent and laser resonator mirror is placed at the distance $(1/2)Z_\mathrm{T}$ due to self-imaging provides good reflection. The comprehensive description of the self-imaging, mode selecting and possibility of phase-locking using Talbot cavity has been recently demonstrated [2, 3, 6].

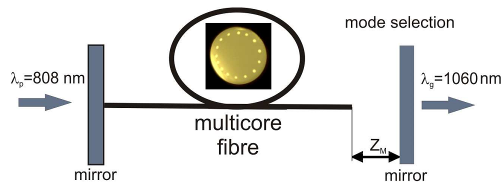

Fig. 1. Basic setup of the Talbot cavity.

The reflection coefficient γ_m which implicates magnitude of the re-injected field amplitude is a function of the propagation distance $Z_\mathrm{prop} = 2Z_\mathrm{M}$ and supermode number. Supermodes with numbers m and $N - m$ possess equal frequencies and losses

$$\gamma_m(z_\mathrm{prop}) = \frac{\left|\int_{-\infty}^{\infty} A_m(x,y,0)\cdot A_m(x,y,z_\mathrm{prop})\,\mathrm{d}x\,\mathrm{d}y\right|}{\int_{-\infty}^{\infty} |A_m(x,y,0)|^2\,\mathrm{d}x\,\mathrm{d}y}. \tag{2}$$

In results of γ_m variation the supermodes possess different self-imaging properties [3]. It is principle of MCF mode selection in an external Talbot cavity. Figure 2 presents amplitude reflection coefficient as function supermode number calculated for the manufactured multicore fibres.

For the fabricated 15 cores and 30 cores optical fibres and mirror placed at their $(1/2)Z_\mathrm{T}$ the in-phase supermode provides high reflection whereas the out-of-phase

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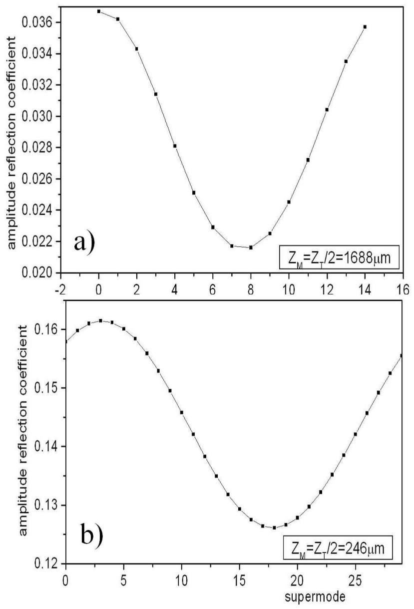

Fig. 2. Calculated amplitude reflection coefficient for $Z_{\mathrm{M}} = Z_{\mathrm{T}}/2$, (a) 15-cores fibre, (b) 30-cores fibre.

supermode suffers high losses. By choosing an appropriate length Z_{M} of the propagation medium one can use the different self-imaging properties of the supermode to discriminate between the eigenmodes of the coupled system and to select the wanted supermode [3].

3. Experiment

The composition of the aluminosilicate glasses used for cores and internal cladding was the following: $57SiO_2$–$(8 - x)PbO$–$6Al_2O_3$–$6B_2O_3$–$3BaO$–$20(Li_2O + Na_2O+K_2O)$–xNd_2O_3 ($x = 0.5$ mol%). Glasses were synthesized by conventional melting and quenching method in argon flow. Pure oxide materials (99.99%) were used to prepare glass batches in the investigated system doped with Nd_2O_3 (99.99%). The glasses were melted in covered gold–platinum crucibles, in an electric furnace, at temperature 1450°C. The melted mass of glass was poured into a brass mould preheated near the glass transition temperature and annealed at temperature range 400–450°C. Transparent and homogeneous glass rods without crystallization were fabricated and applied as cores in multicore double clad optical fibres. Based on the light transmission measurement of samples $20 \times 10 \times 5$ mm^3 performed in the range of 0.4–1.7 μm using ACTON Spectra pro 2300i the absorption cross-section was calculated [7]. Thermal properties of the fabricated glasses were determined by differential scanning calorimeter (Setaram Labsys). The thermal expansion coefficient was measured by a standard dilatometer. Refractive index was measured on a Metricon 2010/M Prism Coupler. The density of the glass was determined by the method of hydrostatic weighing. Rod in tube drawing method was applied to fabricate double clad, 15-core and 30-core optical fibres (Table). Luminescence measurement system consisted of pumping diode — HLU30FAC400-808P ($\lambda = 808$ nm) with optical fibre output (400 nm, NA = 0.22), the laser beam forming system and spectrometer (Ocean Optics HR4000). All the measurements were made at room temperature.

4. Results and discussion

The manufactured glasses are characterized by high infrared transmission coefficient 90% — 3.5 μm and 50% up to 4 μm. Measured indices of refraction are 1.6272–1.6454 depending on the glass composition. Glass density amounts to 3.8 g/cm^3. The softening point temperatures are 470°C and 480°C for core and cladding glass, respectively (Fig. 3). Slight difference between these temperatures (similar viscosity) ensures stability of drawing multicore optical fibre process. Fabricated aluminosilicate glasses are thermally stable. It was confirmed using DSC measurement (Fig. 3).

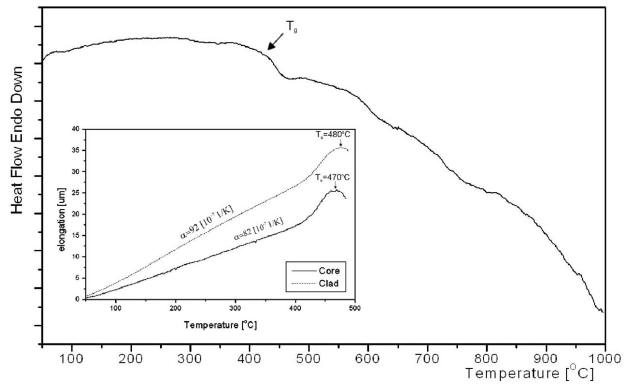

Fig. 3. DSC curve and dilatometer curve (inset) of the fabricated aluminosilicate glass doped with 0.5 mol% Nd^{3+}.

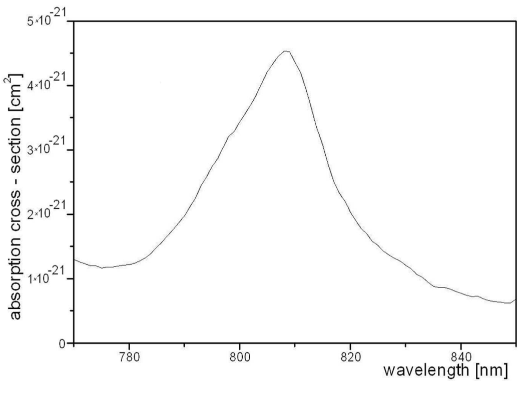

Fig. 4. Absorption cross-section of the manufactured glass doped with 0.5 mol% Nd^{3+}.

The internal mechanical stress of the fabricated fibres is strongly reduced due to similar thermal expansion coefficient of the core and clad glasses. It is especially

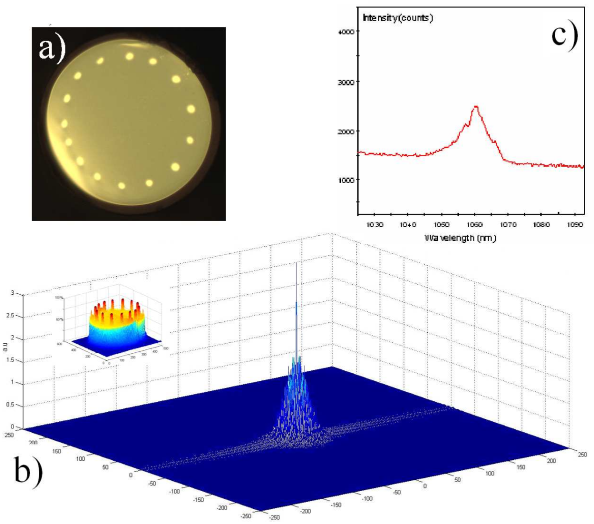

Fig. 5. (a) Cross-section, (b) calculated near and far field (coherent combining), (c) luminescence spectra of the manufactured 15-core optical fibre.

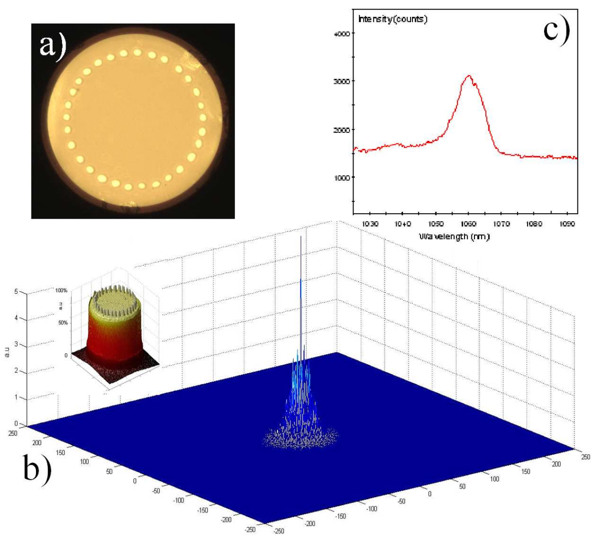

Fig. 6. (a) Cross-section, (b) calculated near and far field (coherent combining), (c) luminescence spectra of the manufactured 30-core optical fibre.

important when manufacturing multicore fibres for fibre laser application. Manufactured glass doped with neodymium ions possesses relative high absorption cross-section (Fig. 4) [7, 8]. It is result of high rare-earth (RE) ions concentration in comparison with silica glass, which accepts 500 ppm of RE elements [8].

Rare-earth ions are easily partitioned by Al^{3+} forming Al–O–RE bonds rather than clustering and forming RE–O–RE bonds. This results in larger spacing among RE ions in the alumina-doped silica host compared to the non-alumina-containing glasses [9–11]. Figures 5, 6 present cross-section, near and far field distribution and luminescence spectra of the manufactured 15-core and 30-core double clad optical fibres.

Fibres were pumped through inner cladding by laser diode AlGaAs (λ = 808 nm). Optical fibre with 30-core possesses greater volume of glass doped Nd^{3+} so can absorb more energy in active glass. Therefore measured luminescence band at 1.06 μm was also greater than in 15-core optical fibre.

Talbot length depends on geometry of multicore fibre. Choice of Z_{M} distance is particularly important problem in construction of Talbot resonator [12 13]. When the mirror distance decreases, discrimination between adjacent supermodes with highest correlation is smaller. For larger distances the intermodal discrimination increases. On the other hand, when distance is large the Talbot resonator suffers strong losses due to radial diffraction [2, 3].

TABLE

Properties of the manufactured multicore fibres doped with Nd^{3+}.

Property	30-cores	15-cores
outer diameter [μm]	350	330
cores diameter [μm]	10	10
$\mathrm{NA_{cores}}$	0.1	0.1
$\mathrm{NA_{clad}}$	0.58	0.58
Nd^{3+} concentration [ions/cc]	2.21×10^{21}	2.21×10^{21}
Talbot length Z_{T} [μm]	3376	493

5. Summary

The paper presents results of investigations in manufacturing of the 15-core and 30-core double clad optical fibres doped with Nd^{3+} ions. The possibility of mode selecting and phase-locking using Talbot cavity applied to fabricated multicore fibres were investigated. Fabricated aluminosilicate glasses used as cores possess good optical and thermal properties and accept high concentration of neodymium (5000 ppm) with neither crystallization effect nor dopant phase separation phenomena. High absorption cross-section of melted RE doped glass enables effective absorption of the pump radiation and gives possibility to reduce the optical fibre length. Double clad multicore optical fibres made from the multicomponent glasses were elaborated. The similarity of the thermal properties of both core and cladding glasses ensure the minimal internal mechanical stress in obtained multicore optical fibres and their high quality especially required for fibre laser application. The luminescence band at 1.06 μm ($^4F_{3/2} \rightarrow {}^4I_{9/2}$) of the manufactured 15-core and 30-core optical fibres were measured. Amplitude reflection coefficient γ_m ($Z_{\mathrm{M}} = Z_{\mathrm{T}}/2$) for both configurations of the fabricated optical fibres were calculated. Fabricated optical fibres placed in Talbot resonator gives possibility to self-imaging and the in-phase mode selection.

Acknowledgments

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References

[1] A.P. Napartovich, *J. Mod. Opt.* **50**, 2715 (2003).

[2] M. Wrage, P. Glas, D. Fisher, M. Leitner, N.N. Elkin, D.V. Vysotsky, A.P. Napartovich, V.N. Troshchieva, *Opt. Commun.* **205**, 367 (2005).

[3] M. Wrage, P. Glas, M. Leitner, D.V. Vysotsky, A.P. Napartovich, *Opt. Commun.* **191**, 149 (2001).

[4] Chu Xing-chun, Zhan Sheng-bao, Zhao Shang-hong, Li Yun-xia, Xu Jie, *Optoelectron. Lett.* **3**, 455 (2007).

[5] S. Serati, H. Masterson, A. Linnenberger, *Proc. 2004 IEEE* **3**, 6 (2004).

[6] D. Dorosz, M. Kochanowicz, *Proc. SPIE* **7120**, 235 (2006).

[7] P. Nandi, G. Jose, *Opt. Commun.* **265**, 588 (2006).

[8] D. Dorosz, J. Swiderski, A. Zajac, *Eur. Phys. J. Special Topics* **154**, 51 (2008).

[9] K. Barczak, T. Pustelny, D. Dorosz, J. Dorosz, *Europ. Phys. J. Special Topics* **154**, 11 (2008).

[10] D. Dorosz, K. Barczak, T. Pustelny, J. Dorosz, *Acta Phys. Pol. A* **114**, A-61 (2008).

[11] Y. Ciao, N. Da, D. Chen, Q. Zhou, J. Qiu, T. Akai, *Appl. Phys. B* **87**, 717 (2007).

[12] T. Pustelny, L. Przybylski, K. Barczak, *J. Phys. IV (France)* **137**, 145 (2006).

[13] K. Barczak, T. Pustelny, A. Szpakowski, M. Błahut, *J. Phys. IV (France)* **129**, 85 (2005).