INSTITUTE OF PHYSICS PUBLISHING PHYSICS IN MEDICINE AND BIOLOGY

Phys. Med. Biol. **49** (2004) 1359–1368 PII: S0031-9155(04)74302-X

Hollow-core photonic-crystal fibres for laser dentistry

Stanislav O Konorov[1], Vladimir P Mitrokhin[1], Andrei B Fedotov[1], Dmitrii A Sidorov-Biryukov[1], Valentin I Beloglazov[2], Nina B Skibina[2], Ernst Wintner[3], Michael Scalora[4] and Aleksei M Zheltikov[1]

[1] Physics Department, International Laser Center, M V Lomonosov Moscow State University, Vorob'evy gory, 119899 Moscow, Russia
[2] Technology and Equipment for Glass Structures Institute, pr. Stroitelei 1, 410044 Saratov, Russia
[3] Institut für Photonik, Technische Universität Wien, Gusshausstrasse 27/387, 1040 Wien, Austria
[4] Weapons Sciences Directorate, US Army Aviation and Missile Command Huntsville, AL 35898-5000, USA

Received 20 October 2003
Published 18 March 2004
Online at stacks.iop.org/PMB/49/1359 (DOI: 10.1088/0031-9155/49/7/021)

Abstract

Hollow-core photonic-crystal fibres (PCFs) for the delivery of high-fluence laser radiation capable of ablating tooth enamel are developed. Sequences of picosecond pulses of 1.06 μm Nd:YAG-laser radiation with a total energy of about 2 mJ are transmitted through a hollow-core photonic-crystal fibre with a core diameter of approximately 14 μm and are focused on a tooth surface *in vitro* to ablate dental tissue. The hollow-core PCF is shown to support the single-fundamental-mode regime for 1.06 μm laser radiation, serving as a spatial filter and allowing the laser beam quality to be substantially improved. The same fibre is used to transmit emission from plasmas produced by laser pulses on the tooth surface in the backward direction for detection and optical diagnostics.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

Transmission of high-energy laser pulses capable of ablating dental tissues is a crucial issue in laser dentistry (Wigdor *et al* 1995, Fried 1999, Strassl *et al* 2002). Flexible and convenient circuits for the delivery of laser radiation are needed to make the solution technologically attractive, which leaves no alternative to fibre-optic beam delivery. Pico- and femtosecond laser pulses have been shown (Mindermann *et al* 1993, Altshuler *et al* 1993, Neev *et al* 1996, Rubenchik *et al* 1996, Serafetinides *et al* 1999) to offer many important advantages over much longer pulses of conventional IR laser-dentistry systems. Short laser pulses

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE	2. REPORT TYPE	3. DATES COVERED
2004	**N/A**	**-**

4. TITLE AND SUBTITLE
Hollow-core photonic-crystal fibres for laser dentistry

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Weapons Sciences Directorate, US Army Aviation and Missile Command Huntsville, AL 35898-5000, USA

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSOR/MONITOR’S ACRONYM(S)

11. SPONSOR/MONITOR’S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release, distribution unlimited

13. SUPPLEMENTARY NOTES
The original document contains color images.

14. ABSTRACT
Hollow-core photonic-crystal fibres (PCFs) for the delivery of high-fluence laser radiation capable of ablating tooth enamel are developed. Sequences of picosecond pulses of 1.06 ìm Nd:YAG-laser radiation with a total energy of about 2 mJ are transmitted through a hollow-core photonic-crystal fibre with a core diameter of approximately 14 ìm and are focused on a tooth surface in vitro to ablate dental tissue. The hollow-core PCF is shown to support the single-fundamental-mode regime for 1.06 ìm laser radiation, serving as a spatial filter and allowing the laser beam quality to be substantially improved. The same fibre is used to transmit emission from plasmas produced by laser pulses on the tooth surface in the backward direction for detection and optical diagnostics.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			
unclassified	**unclassified**	**unclassified**	**UU**	**10**	

allow undesirable crack and shock-wave formation to be avoided and the thermal loads to be minimized, thus improving the quality of crater rims. Physically, these advantages of short pulses are associated with mechanisms of dental tissue ablation, which occurs in the case of short laser pulses through direct plasma formation and subsequent expulsion of material (Mindermann *et al* 1993, Serafetinides *et al* 1999). In view of these growing applications of short laser pulses in dentistry, fibre-optic beam delivery systems face new challenges related to the enhancement of nonlinear-optical processes, which is unavoidable when laser pulses become shorter and which gives rise to undesirable effects in radiation transmission.

Optical nonlinearities along with laser breakdown (Allison *et al* 1985, Trott and Meeks 1990) often restrict the use of standard optical fibres to laser fluences insufficient to ablate dental tissues. Large-core-area silica fibre intended to guide high-power laser pulses (Hand *et al* 1996, Richou *et al* 1997) in addition often have durability problems. Approaches to high-energy laser beam delivery allowing these limitations to be overcome would thus promote laser-dentistry technologies to a qualitatively new level. Hollow-core fibres (Marcatili and Schmeltzer 1964, Zheltikov 2002) allow the fluence of guided laser pulses to be substantially increased relative to standard, silica-core optical fibres, since the gases filling the core of hollow fibres have much higher laser breakdown thresholds and much weaker optical nonlinearities as compared to fused silica. Hollow fibres with an internal polymer layer can be used to guide 30 mJ 6–8 ns pulses of Nd:YAG-laser radiation (Matsuura *et al* 1998). The guidance of 1 ps laser pulses with powers as high as 10 TW has been also demonstrated in earlier experiments (Borghesi *et al* 1998). Cros *et al* (2002) have recently predicted the possibility to use hollow fibres for guiding ultrahigh-intensity subpicosecond laser pulses with no damage on fibre walls. The modes guided by hollow fibres are, however, leaky in their nature, with propagation constants of guided modes in such fibres having nonzero imaginary parts. The magnitude of optical losses in hollow fibres α increases as a^{-3} with a decrease in the fibre core radius a, limiting the guidance length of high-power laser pulses (Marcatili and Schmeltzer 1964).

In this paper, we will demonstrate that hollow-core photonic-crystal fibres (PCFs) offer new solutions to the problem of guiding high-power pulses for laser-dentistry applications. Such fibres, demonstrated for the first time by Cregan *et al* (1999), have a two-dimensionally periodic cladding (two-dimensional photonic crystal) and a hollow core. The photonic band gap in the transmission spectrum of a two-dimensional periodic cladding in these fibres provides high reflection coefficients for electromagnetic radiation propagating along the hollow core of the fibre, allowing specific regimes of waveguiding to be implemented (Cregan *et al* 1999, Konorov *et al* 2002). Hollow-core PCFs, as recently demonstrated by Benabid *et al* (2002), allow the threshold of stimulated Raman scattering in molecular hydrogen filling the fibre core to be considerably lowered, suggesting the way to considerably improve the efficiency of the SRS process. These fibres have been also shown (Konorov *et al* 2003a) to substantially enhance the four-wave mixing of laser pulses in a gas filling the fibre core. In what follows, we will show that sequences of picosecond pulses of 1.06 μm Nd:YAG-laser radiation with a total energy of about 2 mJ can be transmitted through a hollow-core photonic-crystal fibre with a core diameter of approximately 14 μm. Being focused on a tooth surface, these PCF-delivered laser pulses lead to an ablation of dental tissue. The hollow-core photonic-crystal fibre will be shown to support the single-fundamental-mode regime for 1.06 μm laser radiation, serving as a spatial filter and allowing the laser beam quality to be substantially improved. We will finally demonstrate that the same PCF can be used to transmit emission from plasmas produced by laser pulses on the tooth surface in the backward direction for detection and optical diagnostics.

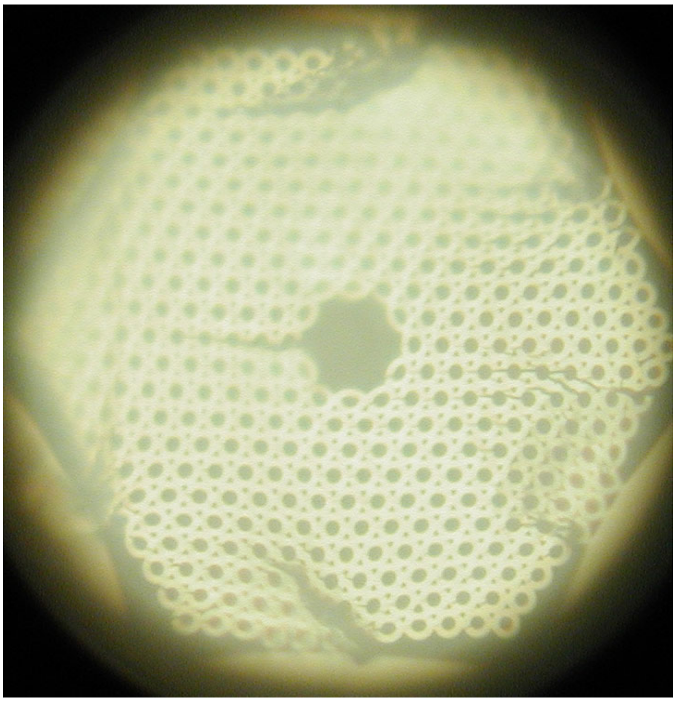


Figure 1. Cross-sectional image of a microstructure fibre with a two-dimensionally periodic cladding consisting of an array of identical capillaries. This periodic cladding supports guided modes in the hollow core of the fibre due to the high reflectivity of a periodic structure within photonic band gaps. The hollow core of the fibre is formed by removing seven capillaries from the central part of the structure. The period of the structure in the cladding is about 5 μm and the core diameter is about 14 μm.

2. Experimental details

The laser system used in our experiments included a flashlamp-pumped Nd:YAG master oscillator with passive mode locking and Q-switching, a system for single-pulse selection, and an amplification stage (Zheltikov *et al* 1994). Mode locking was achieved with the use of a thin-film saturable absorber attached to the rear mirror of the laser cavity. Q-switching, controlled by a fast-response photoelectric multiplier, allowed the stability of pulse parameters to be improved and made it possible to synchronize laser pulses with other sources of optical or electric pulses. The laser system was capable of generating either single pulses with a wavelength of 1.064 μm, duration of about 40 ps, and energy up to 10 mJ (with the single-pulse selection system switched on) or trains of 15–20 40 ps pulses with a total energy up to 5 mJ. These pulse trains were preceded by a microsecond-scale sequence of pulses with an energy two orders of magnitude lower than the energy of the main train of pulses. The time interval between the pulses in the train was equal to 8 ns. The transverse intensity profile in the output laser beam corresponded to the TEM_{00} mode, the beam quality being close to the diffraction limit, with $M \approx 1.1$.

Microstructure fibres were fabricated with the use of a preform consisting of a set of identical glass capillaries. Seven capillaries were removed from the central part of the preform for the hollow core of photonic-crystal fibres. The cross-section image of a fibre fabricated by drawing such a preform is presented in figure 1. A typical period of the structure in the

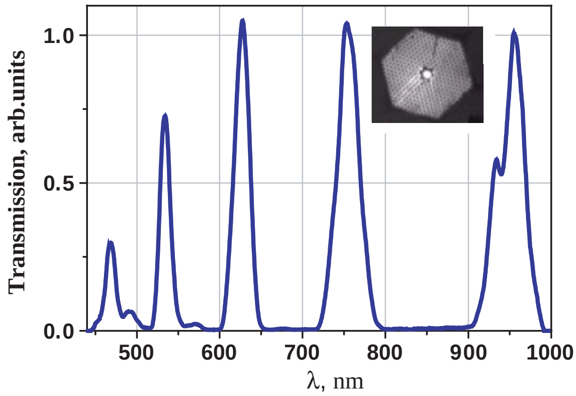


Figure 2. Transmission spectrum of a hollow photonic-crystal fibre (figure 1) with a period of the structure in the cladding of about 5 μm and a core diameter of approximately 14 μm. The inset shows radiation intensity distributions measured in the cross section of the fibre, supporting the fundamental waveguide mode of 633 nm diode-laser radiation.

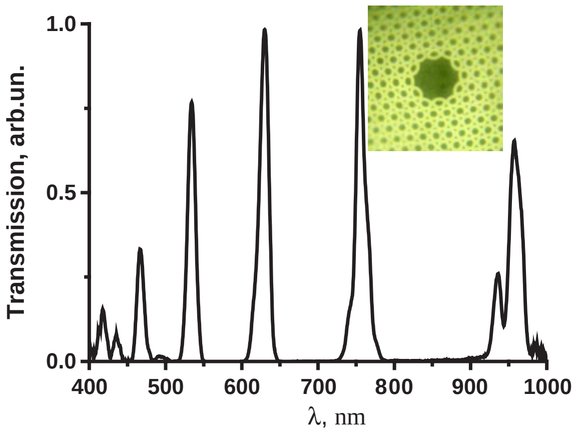


Figure 3. Transmission spectrum of a hollow-core photonic-crystal fibre designed to provide a transmission peak at 532 nm. The inset shows the cross-section image of this fibre.

cladding of the fibre is about 5 μm. The diameter of the hollow core of the fibre is then approximately equal to 14 μm. The length of fibre samples employed in our experiments ranged from several centimetres up to 1 m.

To investigate transmission spectra of hollow-core PCFs, we used a diaphragm to separate radiation transmitted through the hollow core from radiation guided by the cladding. Transmission spectra of PCFs were measured within the range of wavelengths from 400 up to 1500 nm with the use of signal and idler waves generated by a frequency-tunable optical parametric oscillator Solar Laser pumped with 5 ns third-harmonic pulses of a Nd:YAG laser. A standard objective with a numerical aperture (NA) of 0.4 was used to couple radiation into the fibre. Transmission spectra of PCFs displayed characteristic well-pronounced isolated peaks (figures 2–4). Similar peaks in transmission spectra of hollow PCFs have been observed earlier by Cregan *et al* (1999) and Konorov *et al* (2002). The origin of these peaks is associated

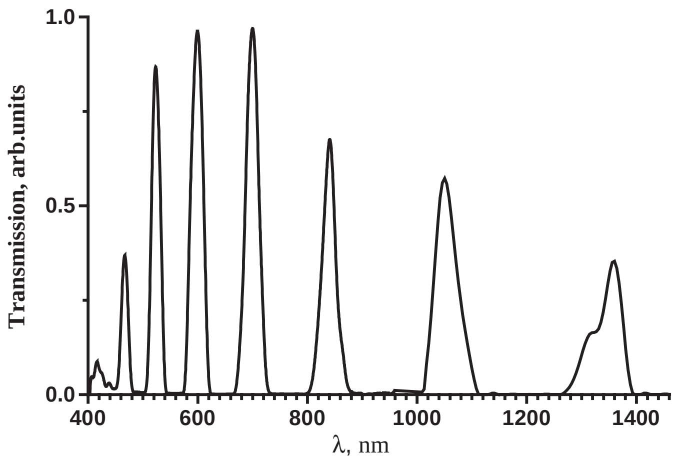


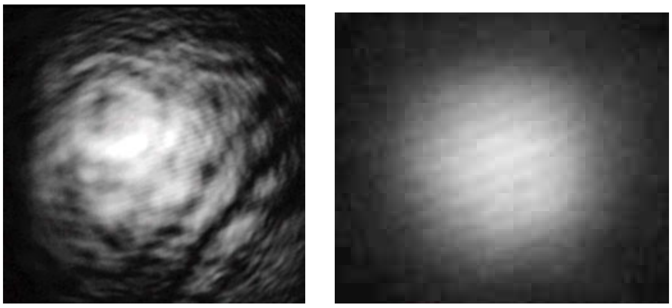
Figure 4. Transmission spectrum of a hollow photonic-crystal fibre employed to guide picosecond pulses of 1.06 μm radiation. The period of the structure in the cladding is about 5 μm.

with the high reflectivity of a periodically structured fibre cladding within photonic band gaps, which substantially reduces radiation losses in guided modes within narrow spectral ranges. Radiation with wavelengths lying away from photonic band gaps of the cladding leaks from the hollow core. Such leaky radiation modes are characterized by high losses, giving virtually no contribution to the signal at the output of the fibre. Modifying the core–cladding configuration of the fibre or even slightly changing the geometric sizes of the cladding, we were able to tune transmission peaks in the spectra of fibre modes (cf figures 2–4), thus achieving maximum transmission for a desirable radiation wavelength. Changing the fibre structure, we could also modify the transverse distribution of radiation intensity in the fibre core, implementing waveguiding in the fundamental and higher order guided modes (see the insets in figures 2 and 3). The cladding of PCFs used in our experiments had a hexagonal unit cell, the pitch of about 5 μm, and a typical air-filling fraction of approximately 15%. Benabid *et al* (2002) have shown recently that, with a modified design of the PCF cladding (fine silica webs arranged in a Kagomé lattice with an air-filling fraction of about 83%), the passbands in PCF transmission can be extended to stretch over the entire visible range.

3. Results and discussion

3.1. Hollow photonic-crystal fibres and their properties

To demonstrate a high transmission of our photonic-crystal fibre within the wavelength ranges corresponding to the photonic band gap of the cladding, we used 633 nm radiation of a diode laser. This wavelength falls within one of the passbands in figure 2, corresponding to the guided modes of our fibre. A 0.4 NA objective was employed to couple laser radiation into the PCF. The maximum throughput achieved with a 10 cm photonic-crystal fibre at 633 nm is estimated as 70%. This result demonstrates that optical losses in hollow-core PCFs are much lower than typical optical losses in leaky modes of standard hollow fibres with a solid cladding. Indeed, the magnitude of optical losses of 633 nm radiation guided in the fundamental mode of a standard hollow fibre with a solid cladding and a core diameter of 14 μm would be on



(a) **(b)**

Figure 5. Spatial filtering with a hollow-core photonic-crystal fibre. Transverse intensity distributions in a 800 nm laser radiation beam (a) at the input and (b) at the output of a 3 cm PCF with a core diameter of approximately 14 μm.

the order of 10–15 cm^{-1}. Optical losses in such a fibre would be unacceptably high even for fibres with a length of a few centimetres.

A high transmission of laser pulses was also achieved in experiments with 532 nm second-harmonic radiation of the picosecond Nd:YAG laser described in section 2. A photonic crystal fibre with a transmission peak at 532 nm was designed for these experiments (figure 3). The cross-section image of this fibre is shown in the inset to figure 3. Less than 20% of 532 nm radiation energy was lost in a few-centimetre long sample of such a fibre.

Experiments on laser ablation of dental tissues were carried out with picosecond pulse trains of 1.06 μm radiation produced by the Nd:YAG-laser system described in section 2. The choice of parameters of laser pulses of 1.06 μm radiation for our experiments was based on the results of earlier theoretical work (Kolevatova *et al* 2003) and experimental studies (Konorov *et al* 2003b). In order to avoid effects related to the ionization of the gas filling the fibre core and the excitation of higher order waveguide modes, we chose to work with trains of 40 ps pulses with an energy around 2 mJ. Such pulse trains were coupled into the hollow core of a 10 cm photonic-crystal fibre with a period of the cladding of approximately 5 μm. The transmission spectrum of this fibre is shown in figure 4. The transmission of photonic-crystal fibres for 1.06 μm radiation in our experiments was on the order of 60%. The attenuation less was estimated as approximately 15 cm (hollow PCFs with much lower radiation losses have been recently demonstrated by Benabid *et al* (2002)). Irreversible effects related to the laser breakdown of PCFs were observed under conditions of our experiments for energies of single 40 ps pulses exceeding 3 mJ.

Analysis of the spatial beam profile at the output of the fibre indicates a robust single-mode waveguiding of 1.06 μm radiation in the fundamental mode. A high quality of beam profiles at the output of the fibre also indicates that the excitation of higher order waveguide modes and ionization effects play a negligible role as laser pulses with above-specified parameters are guided through the fibre, which agrees well with earlier theoretical predictions (Kolevatova *et al* 2003). Due to the fact that higher order air-guided modes are characterized by very high losses, rapidly leaking from the hollow core, PCFs can serve as spatial filters, improving the spatial quality of the laser beam. This filtering capability of PCFs is illustrated in figure 5 by the results of measurements performed with 800 nm radiation. Given a laser beam with a very poor spatial quality at the input (figure 5(a)), we observed a nearly Gaussian-quality beam (figure 5(b)) at the output of a 3 cm hollow-core PCF with a core diameter of approximately 14 μm.

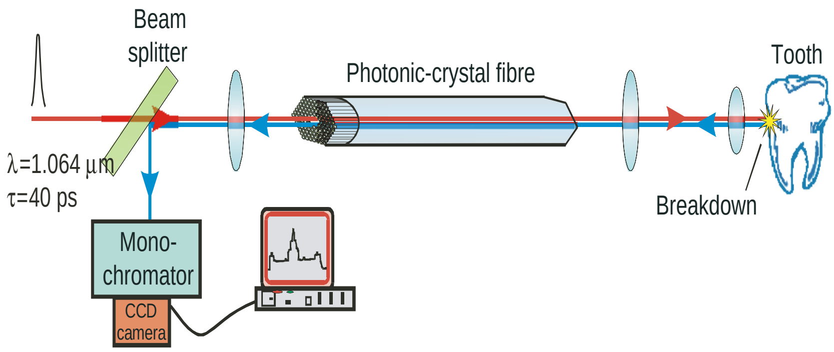


Figure 6. Diagram of the experimental setup for a laser ablation of dental tissue *in vitro*. Picosecond pulses of Nd:YAG-laser radiation are transmitted through a photonic-crystal fibre and are focused on a tooth surface, producing an optical breakdown and ablating dental tissue. Emission from plasmas induced on the tooth surface is transmitted through the fibre in the backward direction and is delivered to the detection system.

3.2. Laser-dentistry applications

Photonic-crystal fibres used in our experiments allowed us to transport trains of 40 ps pulses with a total energy up to 2 mJ. Such an energy of laser pulses coupled into a hollow core of a photonic-crystal fibre with a core diameter of $\sim 14\ \mu$m corresponds to a fluence of 180 J cm^{-2}, which is more than an order of magnitude higher than the typical breakdown threshold of fused silica. Laser radiation transmitted through a hollow PCF and focused upon the surface of a dry carious human tooth *in vitro* (figure 6) induces an optical breakdown, resulting in plasma formation and dental tissue ablation. The laser breakdown was visualized as optical characterization of the ablated enamel surface was carried out. Emission from laser-produced plasmas transmitted through the hollow-core PCF in the backward direction and analysed with a monochromator and a CCD camera (figure 6). The photonic-crystal fibre thus served in our experiments not only to transport the high-power laser pulse to a tooth surface, but also to transmit plasma emission to the system of detection and optical diagnostics.

Figures 7(a) and (b) compare the spectrum of laser-induced breakdown emission from the surface of dental tissue recorded without a fibre (figure 7(a)) with the spectrum of the same signal, but transmitted through the hollow-core PCF (figure 7(b)). Hollow-core PCF, as can be seen from figure 7(b), allow the detection of only those spectral bands of plasma emission that correspond to the transmission peaks of these fibres. With their passbands matched to particular emission lines (figure 7(b)), PCFs, however, can efficiently guide laser-induced breakdown spectroscopy signals, facilitating laser diagnostics of dental tissues. In particular, the 613 nm signal transmitted through a hollow PCF in figure 7(b) corresponds to the emission of calcium ablated from the enamel part of the tooth. This line can be efficiently employed, as shown by Samek *et al* (2001), for caries diagnostics. Thus, although some spectroscopic information is inevitably lost as the backward signal is transmitted through our PCFs, the passbands in transmission can be employed to effectively filter fingerprint spectroscopic lines and even improve the signal-to-noise ratio of the spectroscopic signal.

The laser fluence corresponding to the threshold of optical breakdown of dental tissue ranged from 0.6 up to 1 J cm^{-2} in our experiments, depending on the quality of the tooth surface. These fluences correspond to laser radiation intensities on the order of 10 GW cm^{-2}. The breakdown threshold fluence for dental tissue proved to be highly sensitive to surface defect

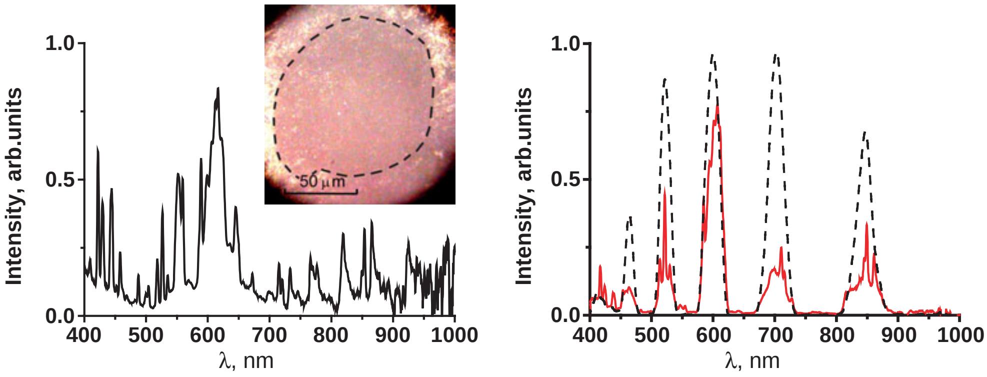


Figure 7. Laser-induced breakdown emission spectra from the surface of dental tissue irradiated with 1.06 μm laser pulses recorded with the use of an optical imaging system without a fibre (a) and a hollow-core PCF signal delivery (b). The dashed line in (b) shows the transmission spectrum of the hollow-core PCF. The inset in (a) shows a microscope image of a tooth surface area with enamel material removed by laser ablation with 60 GW cm^{-2} 40 ps pulses of Nd:YAG-laser radiation transmitted through a hollow PCF.

density, which is typically one of the most important factors influencing plasma formation on surfaces of semiconductors and dielectrics (von der Linde and Schüler 1996, Stuart *et al* 1996, Lenzner *et al* 1998). An image of a tooth surface area with enamel material removed by laser ablation with 60 GW cm^{-2} laser pulses transmitted through a hollow PCF and focused on the tooth surface with a 0.2 NA lens is shown in the inset to figure 7(a). The spot size of the laser beam in these experiments was approximately equal to 15 μm. Scanning the laser beam over the tooth surface, we were able to ablate dental tissue from surface areas on the order of 200 $\times$ 200 μm^2.

4. Conclusion

We demonstrated that hollow-core photonic-crystal fibres offer new solutions to the problem of guiding high-power pulses for laser-dentistry applications. Our experiments have shown that sequences of picosecond pulses of 1.06 μm Nd:YAG-laser radiation with a total energy of about 2 mJ can be transmitted through a hollow-core photonic-crystal fibre with a core diameter of approximately 14 μm. Such an energy of laser pulses coupled into a hollow core of a photonic-crystal fibre with a core diameter of $\sim$14 μm corresponds to a fluence of 180 J cm^{-2}, which is more than an order of magnitude higher than the typical breakdown threshold of fused silica. The results of our experimental studies demonstrate that the excitation of higher order waveguide modes and related beam distortion effects can be avoided in hollow-core PCFs with an appropriate choice of the parameters of fibres and laser pulses. Being focused on a tooth surface, these PCF-delivered laser pulses lead to an ablation of enamel tissue. Hollow-core photonic-crystal fibres are shown to support the single-fundamental-mode regime for 1.06 μm laser radiation, serving as spatial filters and allowing the laser beam quality to be substantially improved. The photonic-crystal fibre thus served in our experiments not only to transport the high-power laser pulse to a tooth surface, but also to transmit plasma emission to the system of detection and optical diagnostics.

Acknowledgments

This study was supported in part by the President of Russian Federation Grant MD-42.2003.02, the Russian Foundation for Basic Research (projects nos 03-02-16929 and 02-02-17098) and the Volkswagen Foundation (project I/76 869). This material is also based upon work supported by the European Research Office of the US Army under contract no 62558-03-M-0033. The research described in this publication was made possible in part by Award no. RP2-2558 of the US Civilian Research & Development Foundation for the Independent States of the Former Soviet Union (CRDF).

References

Altshuler G B, Belashenkov N R, Karasev V B, Skripnik A V and Solunin A A 1993 Application of ultrashort laser pulses in dentistry *Proc. SPIE* **2080** 77–86

Allison S W, Gillies G T, Magnuson D W and Pagano T S 1985 Pulsed laser damage to optical fibers *Appl. Opt.* **24** 3140–7

Benabid F, Knight J C, Antonopoulos G and Russell P St J 2002 Stimulated Raman scattering in hydrogen-filled hollow-core photonic crystal fiber *Science* **298** 399–402

Borghesi M, Mackinnon A J, Gaillard R, Willi O and Offenberger A A 1998 Guiding of a 10-TW picosecond laser pulse through hollow capillary tubes *Phys. Rev.* E **57** R4899–R4903

Cregan R F, Mangan B J, Knight J C, Birks T A, Russell P St J, Roberts P J and Allan D C 1999 Single-mode photonic band gap guidance of light in air *Science* **285** 1537–42

Cros B, Courtois C, Matthieussent G, Di Bernardo A, Batani D, Andreev N and Kuznetsov S 2002 Eigenmodes for capillary tubes with dielectric walls and ultraintense laser pulse guiding *Phys. Rev.* E **65** 026405–12

Fried D 1999 Therapeutic lasers and optical diagnostic technology in dentistry *Opt. Photonics News* **10** 23–9

Hand D P, Su D, Naeem M and Jones J D C 1996 Fiber optic high-quality Nd:YAG beam delivery for materials processing *Opt. Eng.* **35** 502–6

Kolevatova O A, Naumov A N and Zheltikov A M 2003 Guiding high-intensity laser pulses through hollow fibers: self-phase modulation and cross-talk of guided modes *Opt. Commun.* **217** 169–77

Konorov S O, Fedotov A B, Kolevatova O A, Beloglazov V I, Skibina N B, Shcherbakov A V and Zheltikov A M 2002 Waveguide modes of hollow photonic-crystal fibers *JETP Lett.* **76** 341–6

Konorov S O, Fedotov A B and Zheltikov A M 2003a Enhanced four-wave mixing in a hollow-core photonic-crystal fiber *Opt. Lett.* **28** 1448–50

Konorov S O, Fedotov A B, Kolevatova O A, Beloglazov V I, Skibina N B, Shcherbakov A V, Wintner E and Zheltikov A M 2003b Laser breakdown with millijoule trains of picosecond pulses transmitted through a hollow-core photonic-crystal fiber *J. Phys. D: Appl. Phys.* **36** 1375–83

Lenzner M, Krüger J, Sartania S, Cheng Z, Spielmann Ch, Mourou G, Kautek W and Krausz F 1998 Femtosecond optical breakdown in dielectrics *Phys. Rev. Lett.* **80** 4076–9

Marcatili E A J and Schmeltzer R A 1964 Hollow metallic and dielectric waveguides for long distance optical transmission and lasers *Bell Syst. Tech. J.* **43** 1783–810

Matsuura Y, Hanamoto K, Sato S and Miyagi M 1998 Hollow-fiber delivery of high-power pulsed Nd:YAG laser light *Opt. Lett.* **23** 1858–60

Mindermann A, Niemz M H, Eisemann L, Loesel F H and Bille J F 1993 Comparison of three different laser systems for application in dentistry *Proc. SPIE* **2080** 68–77

Neev J, Huynh D S, Dan C C, White J M, Da Silva L B, Feit M D, Matthews D L, Perry M D, Rubenchik A M and Stuart B C 1996 Scanning electron microscopy and ablation rates of hard dental tissue using 350-fs and 1-ns laser pulses *Proc. SPIE* **2672** 250–9

Richou B, Schertz I, Gobin I and Richou J 1997 Delivery of 10-MW Nd:YAG laser pulses by large-core optical fibers: dependence of the laser-intensity profile on beam propagation *Appl. Opt.* **36** 1610–6

Rubenchik A M and Stuart B C 1996 Scanning electron microscopy and ablation rates of hard dental tissue using 350-fs and 1-ns laser pulses *Proc. SPIE* **2672** 250–9

Rubenchik A M, Da Silva L B, Feit M D, Lane S, London R, Perry M D, Stuart B C and Neev J 1996 Dental tissue processing with ultrashort-pulse laser *Proc. SPIE* **2672** 222–32

Samek O, Telle H H and Beddows D C S 2001 Laser-induced breakdown spectroscopy: a tool for real-time, *in vitro* and *in vivo* identification of carious teeth *BMC Oral Health* **1** 1472–80

Serafetinides A A, Khabbaz M, Makropoulou M I and Kar A K 1999 Picosecond laser ablation of dentine in endodontics *Laser Med. Sci.* **14** 168–75

Strassl M, Kasenbacher A and Wintner E 2002 Ultrashort laser pulses in dentistry *J. Oral Laser Appl.* **2** 213–24

Stuart B, Feit M, Herman S, Rubenchik A, Shore B and Perry M 1996 Optical ablation by high-power short-pulse lasers *J. Opt. Soc. Am.* B **13** 459–66

Trott W H and Meeks K D 1990 High-power Nd:glass laser transmission through optical fibers and its use in acceleration of thin foil targets *J. Appl. Phys.* **67** 3297–303

von der Linde D and Schüler H 1996 Breakdown threshold and plasma formation in femtosecond laser-solid interaction *J. Opt. Soc. Am.* B **13** 216–22

Wigdor H A, Walsh J T, Featherstone J D B, Visuri S R, Fried D and Waldvogel J L 1995 Lasers in dentistry *Lasers Surg. Med.* **16** 103–23

Zheltikov A M, Koroteev N I and Fedotov A B 1994 Generation of optical harmonics and frequency mixing in a plasma of optical breakdown *Laser Phys.* **4** 569–78

Zheltikov A M 2002 Ultrashort light pulses in hollow waveguides *Phys. Uspekhi* **45** 687–718