Optical Fiber Technology 41 (2018) 118–124

Contents lists available at ScienceDirect

Optical Fiber Technology

journal homepage: www.elsevier.com/locate/yofte

Regular Articles

Laser-induced nonlinear crystalline waveguide on glass fiber format and diode-pumped second harmonic generation

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ARTICLE INFO

Keywords:
Second harmonic generation
Laser induced crystallization
Fiber design and fabrication
Laser direct writing

ABSTRACT

We report a diode pumped self-frequency-doubled nonlinear crystalline waveguide on glass fiber. A ribbon fiber has been drawn on the glass composition of $50GeO_2$-$25B_2O_3$-$25(La,Yb)_2O_3$. Surface channel waveguides have been written on the surface of the ribbon fiber, using space-selective laser heating method with the assistance of a 244 nm CW UV laser. The Raman spectrum of the written area indicates that the waveguide is composed of structure-deformed nonlinear (La,Yb)$BGeO_5$ crystal. The laser-induced surface wavy cracks have also been observed and the forming mechanism of the wavy cracks has been discussed. Efficient second harmonic generation has been observed from the laser-induced crystalline waveguide, using a 976 nm diode pump. 13 μW of 488 nm output has been observed from a 17 mm long waveguide with 26.0 mW of launched diode pump power, corresponding to a normalized conversion efficiency of 4.4%W^{-1}.

1. Introduction

Since the first observation of second harmonic generation (SHG) from a quartz crystal pumped by a ruby laser in 1961 [1], $\chi^{(2)}$ based second-order nonlinear optical effects have been of great interest, especially for making the efficient, powerful and compact solid state ultraviolet (UV) and visible laser sources. This is currently mainly driven by many industrial applications, for example, micromachining using photolithograph in the semiconductor industry using UV lasers and laser display using the primary colours of red, green and blue (RGB) lasers.

In the simple case of plane waves, non-depletable pump, and perfect phase matching, the second harmonic conversion efficiency $\eta_{2\omega/\omega}$ is proportional to $IL^2(\chi^{(2)})^2$, where I is the fundamental wave intensity, L is the interaction length of the fundamental wave and the harmonic wave, and $\chi^{(2)}$ is the second-order nonlinear coefficient, respectively [2]. To achieve a high conversion efficiency for second harmonic generation (SHG), a long length of a nonlinear material with a high second-order nonlinear coefficient $\chi^{(2)}$ is required. Also small spatial mode size helps to enhance the fundamental wave intensity I. A fiber-based $\chi^{(2)}$ nonlinear medium is thus an ideal medium format. Glass optical fibers have been successfully employed in the long-haul and short-haul optical communications, since (i) glass is a material readily drawn to very long lengths and (ii) the loss of the conventional glass optical fiber is low. Unfortunately, glass is an isotropic material and thus the $\chi^{(2)}$ of an untreated glass is nil. In previous works, thermal or electrical poling methods [3] were applied to fiber to induce a second-order nonlinearity $\chi^{(2)}$ into the originally isotropic glass fiber. A relatively high SHG efficiency (15.2%) as well as high SHG output power (236 mW) was obtained from a 32 cm-long periodically poled silica fiber (PPSF) [4]. However, the second-order nonlinear coefficient d_{33} of the poled silica is very low, only 0.054 pm/V at 1.55 μm [4], almost two orders of magnitude lower than that of the commonly used nonlinear crystal β-BaB_2O_4 (BBO) with a second-order nonlinear coefficient $|d_{22}(1.064\ \mu m)|$ of 2.2 pm/V [5]. Furthermore, electrical poling of the silica fiber requires inserting metal wires with 30 μm diameter into holes around the fiber core [4]. In order to create a quasi-phase-matching (QPM) structure in the PPSF to compensate the mismatch in the phase velocities of the copropagating fundamental wave and harmonic wave, fiber Bragg grating technique had to be employed as well. Both these techniques are time-consuming and inefficient and thus largely limit the useable fiber length in practice.

Glass, known as a supercooled liquid, is thermally metastable. In other words, the glass has higher energy than the crystal, which is a true thermodynamic stable phase. When a type of physical energy, for example the heat, is applied on the glass, and let the glass temperature above its transition temperature T_g, which is the boundary between solid and liquid, the glass will have opportunity to be crystallized. In

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https://doi.org/10.1016/j.yofte.2018.01.015
Received 1 December 2017; Received in revised form 14 January 2018; Accepted 16 January 2018

the crystallization process, the external energy drives the atoms to overcome the energy barrier and consequently transfer through the solid/liquid interface. The atoms from the liquid thus get rearranged in a certain periodic way to form crystal. The traditional glass ceramic technology is such a way to control nucleation and crystallization of glass [6].

In the traditional glass ceramic technology, the whole glass workpiece is reheated in a high temperature furnace. More generally, one can find other alternative approaches to apply certain types of physical energy onto the whole piece of glass or the selected local area on the glass. For example, high-energy laser beam can be focused on the glass and the laser energy is converted to the heat at the selected micron-size domain. The local solid glass becomes into molten state and then the desired crystalline phase can be formed along the laser scanning direction. This method is called as space-selective laser heating [7].

In this work, we report a diode-pumped self-frequency-doubled nonlinear crystalline waveguide on glass fiber format. A ribbon fiber has been drawn on the glass composition of $50GeO_2$-$25B_2O_3$-$25(La,Yb)_2O_3$. Surface channel waveguides have been written on the surface of the ribbon fiber, using space-selective laser heating method. The crystalline nature of the crystalline $(La,Yb)BGeO_5$ waveguide has been analyzed by the micro-Raman spectroscopy. The laser-induced surface wavy cracks have also been observed and the forming mechanism of the wavy cracks has been discussed. Efficient second harmonic generation has been observed from the laser-induced crystalline waveguide, using a CW diode pump.

2. Experiment

2.1. Glass preparation and fiber drawing

Stoichiometric amounts of Yb_2O_3 (Alfa Aesar, 99.99%), La_2O_3 (Alfa Aesar, 99.99%), B_2O_3 (Alfa Aesar, 99.99%) and GeO_2 (Alfa Aesar, 99.99%) were weighed in the composition of $50GeO_2$-$25B_2O_3$-$24La_2O_3$-$1Yb_2O_3$ (mol.%) (Yb1:LBGO glass) to provide a 70-gram batch, and melted in a platinum crucible at 1450 °C for 90 min. The melt was then cast into a stainless steel mould, which was preheated at 600 °C, to form a rectangular slab preform with dimensions of 5 × 15 × 75 mm. The glass slab preform was annealed at 650 °C, around the glass transition temperature T_g, for 2 h and then drawn into ribbon shaped fiber with a width of 450 μm and a thickness of 150 μm. The yield of the fiber draw was greater than 50 m.

The transmission spectrum of a polished Yb1:LBGO glass with a thickness of 5.11 mm was measured by a CARY UV-VIS-NIR spectrometer.

The Differential Thermal Analysis (DTA) curve of Yb1:LBGO glass powder is measured by PerkinElmer DTA7 with a ramp rate of 10 K/min.

2.2. Laser-induced crystalline waveguide on glass fiber format

A CW, single polarization 244-nm frequency-doubled argon-ion laser was employed to create crystalline waveguides on the surface of the ribbon fiber. As schematically shown in Fig. 1, the fibers with a length of 15–20 cm were fixed on a grooved metal plate and mounted on a programmable, motor-controlled high-resolution XYZ translation stage. The collimated UV laser beam was focused onto the surface of the ribbon through a focal lens. The focused spot size was 10 μm in diameter. The XYZ stage moved along the length of the ribbon fiber according to a pre-set program. Laser power focused onto the fiber and the scanning speed of the stage along the fiber length (Y direction in Fig. 1) were the two key parameters in the above process. The power of the exposed UV laser was 20-70mW and the stage scanning rate was 10–120 mm/min. As described in Ref. [8], the absorbed UV laser energy was transformed to thermal energy and the stoichiometric nonlinear crystal $(La,Yb)BGeO_5$ (Yb1:LBGO) was created on the surface of the ribbon fiber, confirmed by the observation of micro-Raman spectroscopy.

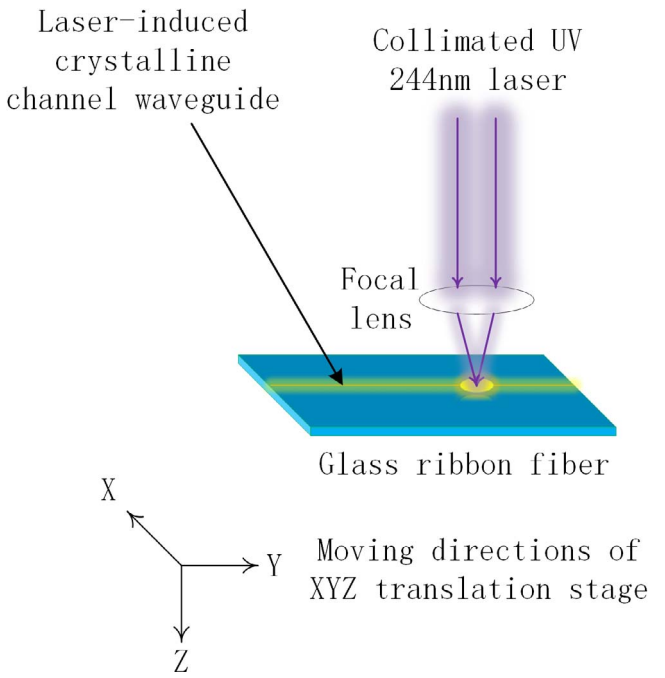

Fig. 1. Schematic diagram of fabricating crystalline waveguide on ribbon fiber using space-selective laser heating.

2.3. Crystallinity characterizations using Raman spectroscopy

In order to investigate the chemical structural change of the laser irradiated area, micro-Raman spectra of various LBGO samples were measured using a Renishaw Raman Microscope with a depolarized 532 nm laser source. With the assistance of a CCD camera on the Raman microscope, the spot size of the 532 nm laser focused on the sample surface was estimated to be between 4 and 5 μm for all the measurements below.

In addition, Yb1:LBGO fibers are reheated for crystallization in a small home-made furnace at 780 °C for a certain period from 0.5 min to 5 h. The Raman spectra of these samples are measured.

2.4. Second harmonic generation

A fiber-pigtailed 976 nm diode laser was used as the pump source for SHG, as seen in Fig. 2. A half wave plate was placed in front of the ribbon fiber to control the polarization of the input light. The collimated pump beam was focused into the crystalline waveguide on a 17 mm long ribbon fiber. A CCD camera was used to monitor the near-field image from the waveguide output, ensuring that the pump light

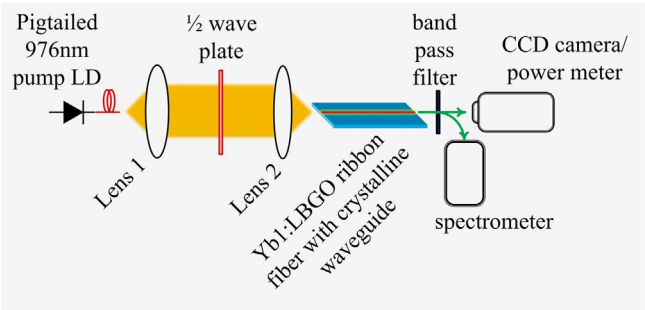

Fig. 2. Schematic diagram of laser diode pumped SHG from crystallized LBGO fiber.