International Journal of Research in Engineering and Science (IJRES)
ISSN (Online): 2320-9364, ISSN (Print): 2320-9356
www.ijres.org Volume 6 Issue 2 ǁ Feb. 2018 ǁ PP.54-58

Generation of Second harmonic in periodically poled silica

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ABSTRACT: *Processes of second harmonic generation in periodically poled germanosilicate fibers were investigated. Dependences of second harmonic generation efficiency on the fundamental radiation characteristics, optical fibers parameters and applied voltage were calculated.*

Keywords: *shots second harmonic generation; thermal poling; periodically poled silica fibers.*

I. INTRODUCTION

Lasers and light-emitting diodes are used as radiation sources in the fiber optic systems. Expansion of operating spectral range of the radiation sources can be based on radiation frequency conversion (harmonic generation, generation of sum and difference frequencies). Nonlinear optical crystals are widely used as frequency converters of optical radiation due to a high coefficient of the quadratic nonlinearity. However such scheme containing both ibers and bulk optical components leads to necessity of adjustment of the optical component and to additional losses on them .

Using optical fibers as a nonlinear medium for frequency conversion in fiber optic systems avoids many disadvantages associated with nonlinear optical crystals. In comparison to nonlinear optical crystals, optical fibers offer inherently lower insertion losses, higher optical damage threshold, greater stability and lesser manufacturing costs. Furthermore, when optical fibers are used in fiber optic systems, there is no additional elements which differ from the fiber refractive index, this simplifies the technological implementation of the system and reduces the optical loss.

II. METHODOLOGY AND DATA

Optical fibers are made of silica glass which is a centrosymmetric material, and therefore does not possess second-order susceptibility in the electric dipole approximation. The symmetry of the silica glass is broken and effective second-order nonlinearity can be present by applying an electric field to a silica sample. Thermal poling is a process to record an electric field in the glass, and thereby create a permanent change of the symmetry.

Compared to other poling techniques, such as CO_2 laser-assisted poling and ultraviolet poling, thermal poling offers a repeatable and reliable method to produce a large second-order nonlinearity and linear electro-optic coefficient in bulk silica and silica fibers [Xu et al. (2001)]. In the process of thermal poling, a fiber is usually heated to temperatures of 200 300°C, while a strong external electrical field 10^7 V/m is applied across the fiber. In this temperature range, alkali ions inside the fiber, such as K^+, Li^+ and especially Na^+, become thermally activated and free to move. Under the influence of the external field, these ions migrate from the anode toward the cathode through the glass matrix [Alley et al. (1999), Quiquempois (2002)]. The ionic current in the glass due to the charge migration is on the order of magnitude of 10 μA upon the application of the external field. After tens of minutes, the current decreases and reaches a steady state value [Myers et al. (1991)]. At this time, the fiber is cooled down to room temperature with the external electric field still applied. Once the fiber reaches room temperature, the external field is removed. Because the mobilities of the alkali ions at room temperature are several orders of magnitude smaller than at elevated temperatures, the alkali ions tend to be “frozen” inside the glass, which results in an internal space electrical field. This internal electrical field, coupled with the intrinsic third-order nonlinear susceptibility of the glass, gives effective second-order nonlinearity.

The electrical field created inside the glass after poling has a spatial profile determined by the internal charge distribution. As the second-order nonlinearity results from the electrical field, it also displays such a spatial profile. This second-order nonlinearity profile is mainly distributed within several micrometers beneath the anode [Myers et al. (1991), Kazansky et al. (1995)], and it is nonuniform throughout the glass. If the portion of the profile with the maximum values of second-order nonlinearity has a good overlap with the core region of the fiber, large effective second-order nonlinearity can be experienced by the optical wave propagating in the fiber. Under such a condition, the poling is efficient and the poled fiber can be used for efficient nonlinear process.

The fibers must meet several requirements for efficient thermal poling. First, as a strong external electrical field is required to break the symmetry of the silica material, high external voltage (5 10 kV) is usually applied along the fiber length. This requires special design of the fiber geometry to let electrodes be incorporated into the fibers. Second, the insertion loss of the fiber might be increased, as the optical mode could be disturbed due to the presence of the electrodes. Thus the relative positions of the fiber core and the electrodes need to be carefully designed to mitigate loss. Third, the core of the fiber must be properly positioned relative to the two electrodes to achieve a good overlap with the induced second-order nonlinearity profile for large effective second-order nonlinearity [Zhang (1999)].

Twin-hole fibers meet these requirements. These fibers have two air holes parallel to the core along the fiber length. Each core can accommodate an electrode, to which, high external voltage can be applied. As twin-hole fibers can be easily spliced to single mode fiber, they only add small coupling losses (< 3 dB) to the fiber systems.

Inserting electrodes into the holes of the twin-hole fiber is the first step of the poling experiment. In the literature, two methods have been reported for inserting electrodes: pumping conductive molten alloys into the holes [Myrén et al. (2004), Myrén, Margulis (2005), Fokine et al. (2002)] and inserting metal wires into the holes manually [Xu et al. (2001), Wong et al. (1999)].

Phase matching between the fundamental and the second harmonic is necessary to improve the efficiency of second harmonic generation, which is achieved through the creation of periodic electric-field-induced-second-harmonic generation in optical fibers (creation of periodically poled silica fibers). Period of the structure and length of the periodically poled silica fiber determine the wavelength range of the pump for the condition of quasi-phase matching [Fejer et al. (1992)]. However, direct periodic poling is not readily available for twin-hole fibers. Alternatively, the quasi-phase matching is achieved by erasing the poled region periodically using ultraviolet light after uniform second-order nonlinearity is recorded in the fiber.

III. RESULTS

Experimental samples of periodically poled germanosilicate fibers were made on the basis of the Fiber Optics Research Center of the Russian Academy of Sciences (FORC RAS, Moscow). Germanosilicate fiber segments ([GeO_2] = 13.5 mol.%) with a core diameter of 4 mm and the difference in refractive indices of core and cladding ắn = 0.0075 were used as samples for thermal polling. Fiber was specially designed with two air holes of 50 µm diameter in its cladding region on each side of the core. The diameter of the twin-hole fiber was 125 µm, the same as that of the standard single mode fiber, that allows the twin-hole fiber to be easily spliced to the standard fiber optical system with low coupling loss.

Gold-coated tungsten wires of 25 µm diameter were inserted into the holes (one wire in each hole) as electrodes manually. Fibers fixed under a microscope, and metal wires were threaded directly through the side-openings on the fiber into the holes by hand.

In the process of thermal poling, germanosilicate fibers were heated to temperature of 220 °C, while external electrical field 8 kV was applied across the fibers. After 20 minutes external field was removed and the fibers were cooled down to room temperature.

Quasi-phase matching for second harmonic generation in ȝ § 532 nm was achieved through point-by-point periodic (ä = 43, 6 µm) ultraviolet erasure (ȝ = 244 nm, P = 10 J/cm^2) over a record lengths of 15 cm and 32 cm .

The peak of the second harmonic experimentally recorded with use of the optical spectrum analyzer. Long-wavelength of the radiation source spectrum was used as pump. The magnitude of power spectral density at maximum peak of the second harmonic ($P_{2À}$) was a measure of the second-order nonlinearity in the periodically poled samples.

Power value of the second harmonic increases with the length of the fiber.The absolute value of the second harmonic power for the fiber length of 32 cm was 1.86 times larger than for fiber length of 15 cm.

Dependences of second harmonic generation efficiency on the content of GeJ_2, wavelength of the fundamental radiation, period of the second-order nonlinearity grating, magnitude of the applied voltage, were calculated for poled silica fibers.

Refractive indices for Ge-doped poled fibers were calculated according to Sellmeier equation:

$$n^{2} \; O \quad 1 \text{¦}^{3} \; \frac{A_i O^{2}}{2 \qquad 2} \qquad (1)$$

i 1 O l$_i$

where Ⱥ$_i$, l$_i$ are Sellmeier coefficients; Ȝ, l$_i$ are expressed in micrometers (μm).

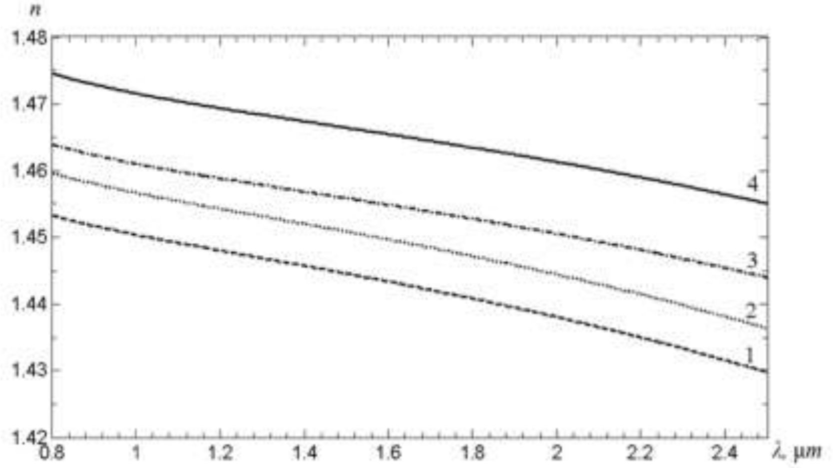

Fig. 1. Dependence of refractive indices on wavelength for silica fibers with [GeɈ$_2$]:

1 – 0 mol.% , 2 – 4 mol.%, 3 – 7 mol.% , 4 – 13.5 mol.%.

Second harmonic generation could be achieved via quasi-phase- matching, which can be realized in twin-hole fibers by recording a periodic second-order nonlinearity. Period of the structure and length of the fiber determine the wavelength range of quasi-phase-matching.

After uniform second-order nonlinearity was recorded in the samples, the selected parts of the uniformly poled fiber were exposed to ultraviolet light, so that the second -order nonlinearity could be erased periodically. The period was determined by the coherence length. As a result, the condition of quasi-phase matching for the second harmonic generation of light at 532 nm was provided.

The spatial length over which the radiation changes from completely in phase to out of phase by ʌ/2 is defined as

the coherence length (beat length) of the process:

L$_c$ $\left|\frac{S}{'k}\right|$ (2)

Coherence lengths for fibers with various GeO$_2$ contents for Nd:YAG laser radiation (Ȝ = 1064 nm) were determined from the dependence of coherence length on wavelength Ȝ (Figure 2).

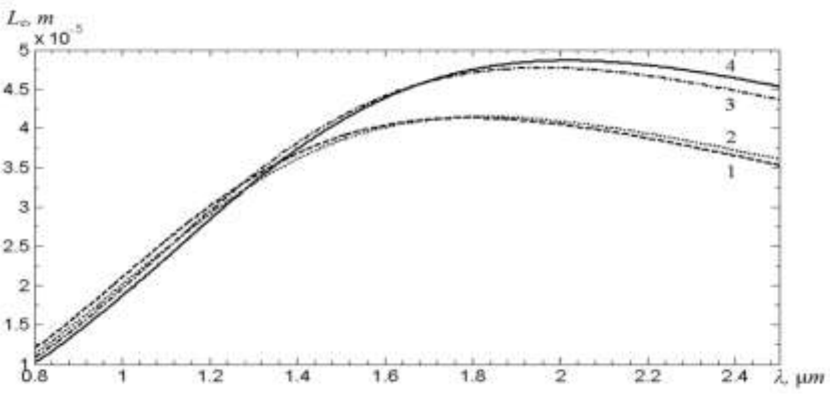

Fig. 2. Dependence of coherence length on wavelength Ȝ for silica fibers with [GeɈ$_2$]:

1 – 0 mol. %, 2 – 4 mol.%, 3 – 7 mol.% , 4 – 13.5 mol.%.

With quasi-phase matching, the second harmonic generation efficiency is defined by the period of the second-order nonlinearity grating ä = 2m·L_c (m is an odd number) [Myrén (2005)] and length of the periodically poled silica fiber.

Intensity of converted radiation of frequency 2Ȧ is given by

$$I(2\dot{A})\ \ AI_0^2(\dot{A})\ \frac{\sin^2('kl/2)}{('k/2)^2}, \qquad (3)$$

where A – constant is proportional to the squared component of nonlinear susceptibility tensor, I_0(Ȧ) – intensities of fundamental radiation with frequency Ȧ, l – length of silica fibers; åk – disturbance of phase matching. Dependences of second harmonic generation efficiency on wavelength for periodically poled silica fibers with various GeO_2 contents are shown in Figure 3. The period of the structure is equal to even number of coherence lengths for the fundamental radiation wavelength of 1064 nm. Second harmonic generation efficiency in periodically poled silica fiber is reduced with an increase in the odd number m.

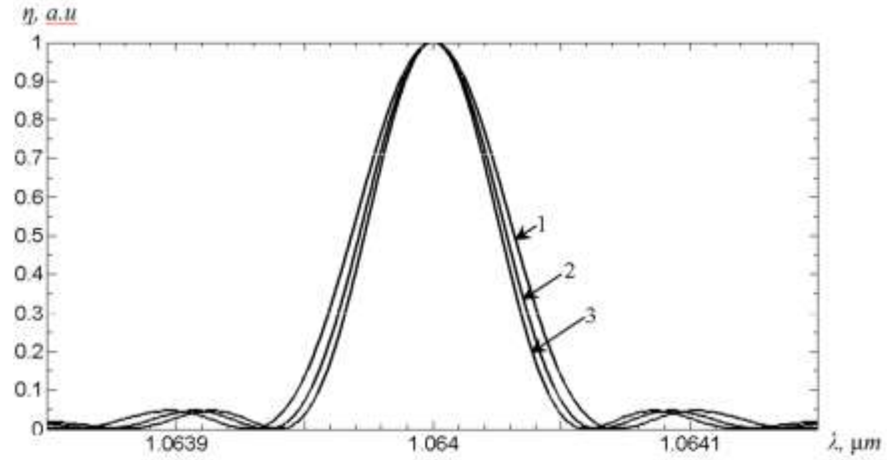

Fig. 3. Dependence of second harmonic generation efficiency on wavelength of Nd:YAG-laser at m=1 for silica fibers

lengths of 32 cm with [GeЈ$_2$]: 1 – 4 mol.%, = 2,3023·10^{-5} m; 2 – 7 mol.% , = 2,2704·10^{-5} m; 3 – 13,5 mol.% , = 2,1683·10^{-5} m; – coherence length for Ȝ= 1064 nm

Externally applied electric field changes the refractive index of the poled silica fiber, that results to a change of coherence length and wavelength of quasi-phase matching. Dependences of second harmonic generation efficiency on applied voltage (Figure 4) show that maximum second-harmonic generation efficiency can be obtained by changing the applied voltage.

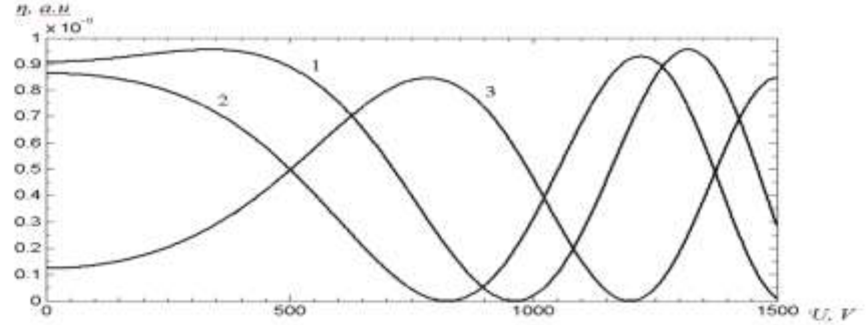

Fig. 4. Dependence of second harmonic generation efficiency for poled silica fibers lengths of 15 cm on applied voltage; fibers with [GeЈ$_2$]:

1 – 4 mol.%, 2 – 7 mol.%, 3 – 13.5 mol.%; fundamental wavelength ʒ = 1064 nm

Dependence of second harmonic generation efficiency on fundamental wavelength ʒ for periodically poled silica fibers (Figure 5) shows that, there is maximum of the conversion efficiency at th corresponding wavelength for each particular voltage.

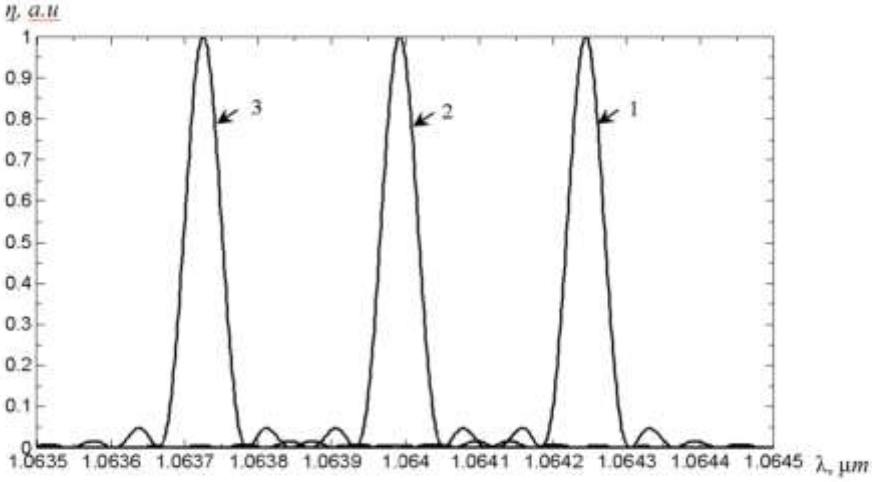

Fig. 5. Dependence of second harmonic generation efficiency on fundamental wavelength ʒ for periodically poled silica fibers [GeJ$_2$]=13.5% (ä = 85,2·ʒm) at applied voltage: 1 – U = 5,22 kV; 2 – 5,52 k V; 3 – 5,82 kV

IV. CONCLUSION

Second harmonic generation efficiency in periodically poled silica fibers depends on the fundamental radiation characteristics, optical fibers parameters and applied voltage. By choosing a period of the second - order nonlinearity grating, that matches the coherence length of the fiber, it is possible to enhance the conversion efficiency by quasi-phase matching. Second harmonic generation efficiency is directly proportional t the length of the second-order nonlinearity grating, which is recorded in periodically poled silica fiber and inversely proportional to the number of coherence lengths m from one period of the second-order nonlinearity grating. The efficiency of second harmonic generation of the laser source radiation can be increased by using an applied voltage.

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