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Effect of fiber stretch on quasi-phase-matching for second-harmonic generation in thermally poled twin-hole silica-glass fiber

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ABSTRACT

Optimization of the quasi-phase-matching (QPM) for second-harmonic generation in thermally-poled twin-hole fiber was performed by stretch of the fiber. The periodic structure for QPM was fabricated by erasure of the second-order nonlinearity by exposure with ultraviolet light through a mask. Exposures with a KrF excimer laser and a low-pressure mercury lamp were compared. The fundamental-wave source was a Q-switched Nd:YAG laser. The dependence of the second-harmonic output on the strain induced by the stretch of the fiber was measured. For periodic depoling by excimer-laser exposure, the second-harmonic power increased by a factor of up to 4 by the stretch. For periodic depoling by mercury-lamp exposure, the maximum increase by the stretch was also by a factor of up to 4. The fiber stretch was effective for fine tuning of QPM for poled fibers.

1. Introduction

Silica glass has an excellent optical transparency and thus has been used for optical fibers, optical components and thin-film waveguides. The optical nonlinearity in fibers has also been used for Raman amplification, soliton generation and so on. Second-harmonic generation (SHG) [1] is one of the most useful nonlinear optical phenomena, and it has been applied mainly for conversion of infrared laser light to visible light. However, the second-order nonlinearity that generates the SH wave is limited to materials without inversion symmetry. Although glasses have inversion symmetry, SHG in an optical fiber was demonstrated with prolonged exposure in 1986 [2]. SHG in bulk silica glass was also found by applying a high electric field at an elevated temperature (thermal poling) [3]. The second-order nonlinearity was generated in a thin layer of several micrometers near the surface of the anode side of the applied voltage [3]. Ultraviolet poling was also reported for bulk silica [4]. The mechanisms of thermal poling have been discussed with migration of ions movable at a high temperature. However, the detailed mechanisms have been unsolved.

On the other hand, phase matching [1] is necessary for efficient SHG. For crystal waveguides such as $LiNbO_3$, a periodic inversion of the polarity of the nonlinearity is possible, and quasi-phase-matching (QPM) is performed. Although the inversion of the nonlinearity is difficult for fibers, periodic poling with periodic metal electrodes [5,6] was performed. A conversion efficiency to SH light of greater than 20% was reported using periodic metal electrodes evaporated on a D-shaped fiber [6]. Another method is the periodic erasure of the nonlinearity by depoling. The depoling was found for exposures with ultraviolet laser light at 193 nm [7] and 248 nm [8]. The periodic depoling after uniform poling has been performed on fibers [9–12]. Twin-hole fibers are also suitable for applying a high electric field to the core, and a special polishing is not necessary. Twin-hole fibers have been used for SHG [10–12]. Using a 244-nm argon-laser SH as a light source, periodic exposure was performed for twin-hole fiber, and an efficiency of 15.2% was reported [12]. The optimum QPM period varies with the fundamental wavelength. Compression of a QPM fiber has already been reported [11], where the QPM fiber was embedded in polymeric materials on a steel beam, and by bending the beam toward the inside, a wide tuning range of 45 nm has been obtained [11]. On the other hand, QPM with a low pressure mercury lamp (254 nm) has been studied on a D-shaped fiber [9]. A low pressure mercury lamp is attractive as a low-cost ultraviolet source.

The authors reported SHG in a thermally-poled twin-hole fiber and performed QPM with a KrF excimer laser [13]. The authors also studied QPM with a low-pressure mercury lamp [14]. As the fundamental wavelength of the authors was fixed to 1.06 μm, a fine tuning of the effective QPM period to the coherence length was expected to increase the SH

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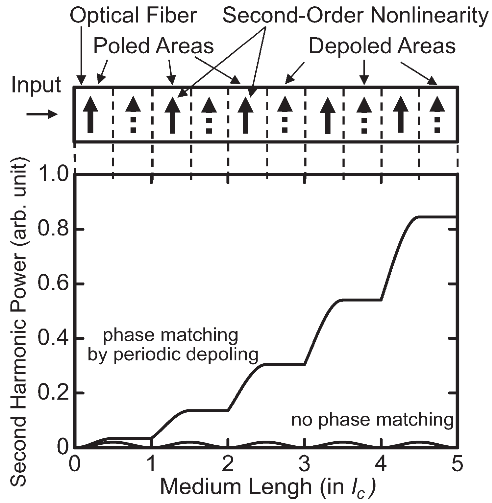

Fig. 1. SHG in the second-order nonlinear medium with and without QPM by periodic depoling. The second-order nonlinearity is erased periodically with an ultraviolet exposure. l_c is the coherence length.

output. In this paper, the effect of the stretch of the fiber was studied on a periodically depoled thermally poled twin-hole fiber to optimize QPM and obtain the increase in the SH output. Periodic depoling with a KrF excimer laser and a low-pressure mercury lamp were compared.

2. Theory

Fig. 1 shows the SH power by the second-order nonlinearity in a nonlinear material. The SH and the fundamental waves travel with different phase velocities due to chromatic dispersion. When the second-order nonlinearity is uniform all along the material, the generated SH waves cancel each other, and the output remains very low. In contrast, if the second-order nonlinearity is distributed periodically, the generated waves increase with the distance; or remain the same where there is no nonlinearity. The periodic distribution can be realized by periodic depoling by ultraviolet-light exposure. For crystal waveguides, the polarity of the nonlinearity is inverted periodically, and the SH output continues to increase in both positive and negative nonlinear areas. The electric field of QPM by depoling is half that of the conventional QPM for crystal waveguides, and the optical power is one-fourth that of the latter.

The coherence length l_c in Fig. 1 is given by [1].

$$l_c = \frac{\lambda}{2\left(n_{eff}^{2\omega} - n_{eff}^{\omega}\right)}, \tag{1}$$

where $n_{eff}^{2\omega}$ and n_{eff}^{ω} are the effective refractive indices of the core mode at the SH and the fundamental wavelengths, respectively, and λ is the fundamental wavelength in vacuum. The optimum QPM period equals l_c except for higher-order matching.

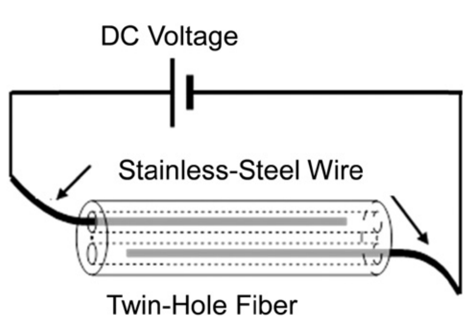

Fig. 2. Method of thermal poling of a twin-hole fiber.

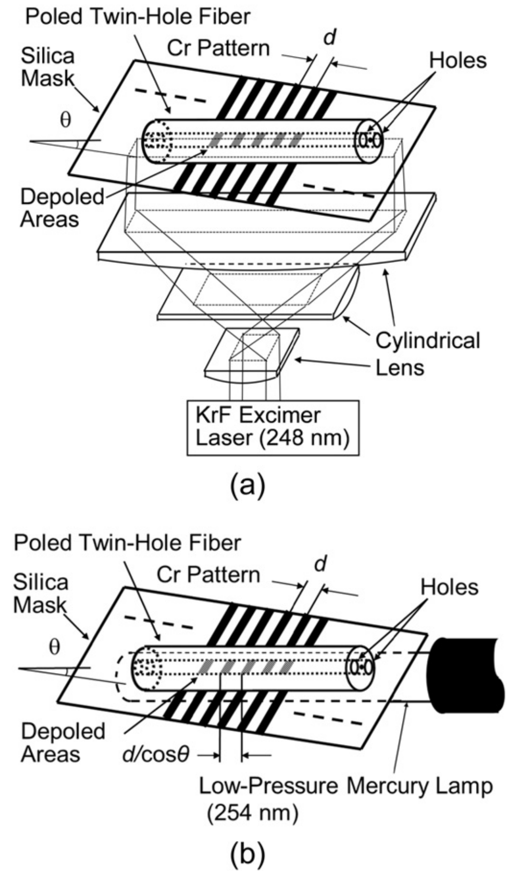

Fig. 3. Methods of periodic depoling with a KrF excimer laser (a) and a low-pressure mercury lamp (b).

When the effective grating period Λ is smaller than l_c, the fiber should be stretched to optimize QPM. The refractive index decreases with the stretch by photoelastic effect. The effective photoelastic constant p_e is given by

$$p_e = \frac{n^2}{2}\{p_{12} - \nu(p_{12} + p_{11})\}, \tag{2}$$

where n is the refractive index, ν is the Poisson's ratio and p_{11} and p_{12} are the strain-optic coefficients [15], and p_e for fused silica is 0.22 [15, 16]. If the same value of p_e is assumed for both the fundamental and SH wavelengths, then the strain for the optimum QPM is given by.

$$\varepsilon = \frac{\frac{l_c}{\Lambda} - 1}{1 - p_e}, \tag{3}$$

where Λ is the effective grating period. Thus, the optimum fiber strain is 1.28 times that expected from the difference between the depoling period and the coherence length. However, the wavelength dependence of the refractive index in Eq. (2) should be considered because the

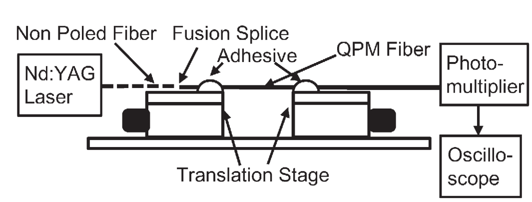

Fig. 4. Experimental set-up for stretch of a fiber to optimize QPM by periodic depoling.