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Femtosecond-pulse inscription of fiber Bragg gratings with single or multiple phase-shifts in the structure

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ABSTRACT

In this work, long high-quality fiber Bragg gratings with phase shifts in the structure are inscribed directly in the optical fiber by point-by-point technique using femtosecond laser pulses. Phase shifts are introduced during the inscription process with a piezoelectric actuator, which rapidly shifts the fiber along the direction of its movement in a chosen point of the grating with a chosen shift value. As examples, single and double π phase shifts are introduced in fiber Bragg gratings with a length up to 34 mm in passive fibers, which provide corresponding transmission peaks with bandwidth less than 1 pm. It is shown that 37 mm π-phase-shifted grating inscribed in an active Er-doped fiber forms high-quality DFB laser cavity generating single-frequency radiation at 1550 nm with bandwidth of 20 kHz and signal-to-noise ratio of >70 dB. The inscription technique has a high degree of performance and flexibility and can be easily implemented in fibers of various types.

1. Introduction

Fiber Bragg gratings (FBGs) with phase shifts in the structure have a wide range of applications in sensor and laser devices: distributed-feedback [1] and multiwavelength [2] fiber lasers, optical sensors for simultaneous temperature/stain measurements [3], high-sensitivity ultrasonic detectors [4], optical signal processing and filtering elements [5,6]. The standard method of a phase-shifted FBG (PSFBG) inscription is based on the UV exposure via a special phase mask [7], or by means of a uniform phase mask displacement in the process of inscription [8]. Moreover, it has been shown that PSFBG can be created by post-processing of a uniform FBG – additional phase shift can be introduced in a limited fiber segment by the core overexposure with UV radiation [9], or by the impact on the fiber cladding with CO_2 irradiation [10], or electric arc discharge [11].

The technology of femtosecond (fs) laser modification of refractive index (RI) in transparent materials enhances functional capabilities of FBG inscription due to the specifics of fs laser pulses absorption mechanism. For example, nonlinear absorption makes it possible to modify non-photosensitive materials and to inscribe FBGs through the fiber plastic coating, which is transparent for IR fs radiation. In addition, the fs technology allows one to inscribe FBG directly, without using a phase mask. There are two main ways of direct FBG inscription: point-by-point [12] and core-scanning [13–15] techniques. For FBG inscribed with point-by-point technique, when each pulse "writes" one grating pitch, a phase shift in the grating was obtained by introducing a delay to the clock source which controls the laser pulse repetition rate [16] (1 kHz in this case), or by decimating 5 kHz laser pulses using electro-optical modulator [17]. It is shown in [18] that the PSFBG also can be created by using high-frequency (500 kHz) laser and acousto-optical modulator releasing fs radiation in pulse-bunch mode. In this case, one single pitch of the grating is created by short series of fs pulses and the length of the series determines effective RI change in the focal volume. In addition, fs inscription of PSFBG can be carried out through the phase mask, as in the case of UV exposure.

However, there are a number of restrictions imposed on the mentioned methods. For the phase mask inscription technique, the FBG's resonant wavelength is limited to a very narrow spectral range for a given phase mask. The point-by-point technique requires laborious fiber alignment procedure and minimization of errors accumulated during the fiber translation. Longitudinal misalignments of fs modifications introduce phase errors and

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transversal ones disturb FBG's coupling coefficient. For this reason, it was difficult to achieve high-quality PSFBG of the required length (30–50 mm [19]) to form a DFB laser cavity by point-by-point writing technique. Recently, the method of correcting misalignment errors during the FBG inscription was proposed [20]. As a result, high-quality FBGs with length of 50 mm were fabricated in polyimide-coated fiber.

In this paper, we propose new technique to introduce arbitrary-controlled phase shifts in the FBG structure. In this technique, the phase shift is provided by the rapid longitudinal displacement of the fiber using a piezoelectric element during the FBG inscription process. The demonstrated technique along with the fiber auto-alignment system makes it possible to create long high-quality PSFBGs with high productivity and flexibility. To the best of our knowledge, the first DFB fiber laser based on point-by-point fs inscribed PSFBG is demonstrated in the present paper. Advantages of the fs inscription technology make this technique attractive for fabrication of fiber devices and passive components with advanced performance.

2. Experimental setup

In this work, we use a basic setup previously described in [20] in detail. The setup is based on Pharos 6 W (Light Conversion Ltd) fs laser (λ = 1030 nm, Δt = 230 fs, f = 1 kHz), Aerotech ABL1000 air-bearing linear stage with a travel range of 100 mm, and 100X Mitutoyo Plan Apo NIR HR (NA = 0.7) focusing objective. Two different fused silica glass ferrules, through which the fiber was drawn, are used in the experiment. The first one to draw polyimide-coated fiber (ID = 152 µm, OD = 3 mm) and the second one to draw uncoated fiber (ID = 127 µm, OD = 3 mm). The simplified scheme of the setup is presented in Fig. 1. The fiber clamp, which previously was fixed at linear stage to inscribe uniform FBGs, was set on piezo actuator (Piezo2) with movement direction along the linear stage. It is noteworthy that piezoelectric elements have been widely used in interferometric FBG inscription methods to adjust the position of the phase mask [8] or to control tension preload of a fiber [21]. During the point-by-point FBG inscription, at a given point, the constant voltage (ΔU = 5.3 V) is applied to the actuator, which provides additional fiber displacement in the direction of its movement ($\Delta x_{gap} \simeq 0.27$ µm). The value is approximately corresponds to $\Lambda_{FBG}/2$, where Λ_{FBG} = 0.535 µm is a period of a 1st order FBG inscribed in this work. The magnitude of the bias voltage is controlled by the value supplied to the actuator and can be chosen within a rather large range (up to tens of microns). Importantly, for the accurate phase shift assignment, the transition time of the piezo actuator (about 200 µs in our case), should be less than the laser pulse repetition interval (1 ms in our case) (Fig. 2).

The PSFBGs with characteristics discussed in the next section are inscribed in polyimide-coated passive fiber (Fibercore SM1500(9/125)P) and final experiments are performed with an

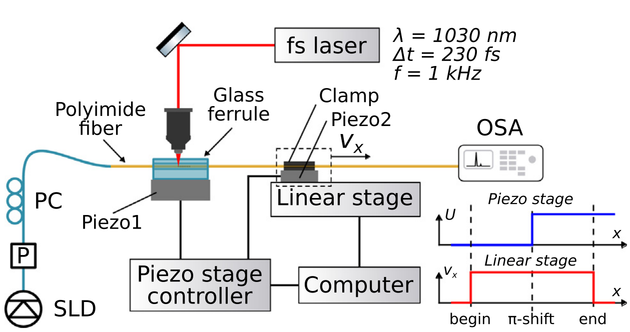

Fig. 1. Experimental setup for PSFBG inscription.

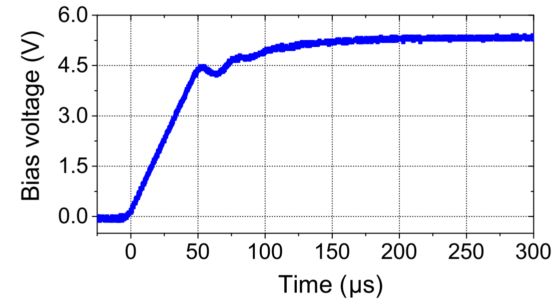

Fig. 2. The voltage on piezo actuator forming the phase shift.

Er-doped active fiber. For positioning of the fiber core relative to the writing beam, the ferrule is placed on piezo actuator (Piezo1) driven by the controller providing auto-alignment [20].

To measure spectra of PSFBGs two different interrogation schemes are used. The first one (Fig. 1), based on superluminescent diode (SLD), polarizer (P), polarization controller (PC) and Yokogawa AQ6370D optical spectrum analyzer (OSA), is used to control spectra during the experiment. The second one (Fig. 3) utilizes single-frequency tunable distributed feedback (DFB) fiber laser with spectral linewidth <10 kHz to resolve narrow spectral resonances associated with the phase shifts in PSFBG structure. In order to ensure the tuning of DFB laser wavelength, the laser cavity, which is π-phase-shifted FBG inscribed in the active fiber, was continuously stretched by means of a piezoelectric element. 15 Hz ramp voltage signal, which was fed to the piezo, provided a stretching of the resonator by $\sim$100 µε and tuning of the wavelength by $\sim$50 pm. Stabilization of the spectral position of the laser scanning domain was ensured by maintaining a constant temperature using the Peltier thermocontroller. The spectral position of the studied PSFBG and the wavelength of DFB laser are monitored by OSA1 and OSA2 spectrum analyzers, respectively. With OSA2 we monitor the spectral position of the tunable laser relative to the investigated FBG. The polarization state of the DFB laser relative to the PSFBG polarization axis is provided by polarization controller (PC). The laser light transmitted through the PSFBG is measured by high-speed photodetector (PD) and oscilloscope (OSC).

3. Results

Fig. 4 shows transmission spectra of the PSFBG with the length of L_{FBG} = 8.6 mm and π phase shift placed in the middle of the grating. The energy of fs laser pulses during the inscription was 165 nJ. Since point-by-point fs inscribed FBGs have a relatively large value of birefringence, transmission spectra were measured for the fast and slow polarization axes. From the difference in the spectral positions $\Delta\lambda_{pol} \simeq 37$ pm the value of birefringence associated with the FBG can be estimated as $\delta n = \Delta\lambda_{pol}/2\Lambda_{FBG}$ = 3.46×10^{-5}. The spectral width of the transmission bandwidth at -3 dB level is 7.5 pm and 15.5 pm pm for the fast and slow polarization axes,

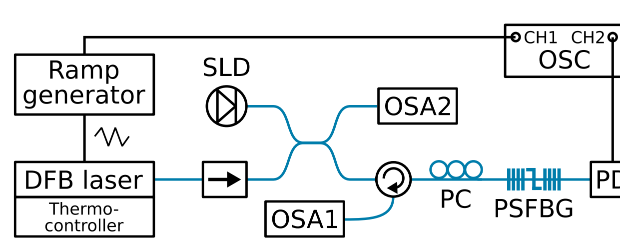

Fig. 3. PSFBG interrogation scheme using single-frequency tunable DFB fiber laser.