Single-polarization distributed feedback fiber laser with multiple phase shifts

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Distributed feedback fiber lasers with multiple phase shifts are fabricated and investigated. Single longitudinal mode lasers with single polarization are obtained by the structure design with two phase shifts. No obvious differences in laser performance, including pump threshold, slope efficiency, relative intensity noise, spectral linewidth, and polarization state, are observed for the presented distributed feedback fiber laser structures with different phase shift locations.

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Distributed feedback fiber laser (DFB-FL) emitting 1.55 μm band laser has been extensively studied and developed for its unique characteristics such as narrow-spectral linewidth, robust single longitudinal mode operation, and compact dimension[1–11]. The normal DFB-FL has a uniform phase-shift grating with a single π phase shift. However, it exhibits an intense space hole burning (SHB) effect inside the grating for its DFB structure and opposite phase around the phase shift spot. Many reports and publications are available on this phenomenon in theory and experiment[6–11]. SHB inside the laser cavity is not required because it deteriorates the laser performance in some conditions such as external disturbance and extreme high pump. SHB of DFB laser diode (LD) can be reduced by multiple phase shift structure, coupled phase-shifted structure, or chirped structure[12–14]. Very few studies are available on reducing SHB for DFB-FL. Therefore, introducing multiple phase shifts into DFB-FL is an effective option[10] to reduce SHB effect. Multiple phase shifts in DFB-FL have multiple power peaks with low values in cavity and flatten the whole power distribution inside the cavity. However, few experiments have been reported for the rigorous technique to produce the precise phase shifts. We present the DFB-FLs with two $\pi/2$ phase shifts at different positions, fabrication of the multiple phase-shifted DFB-FLs is reported and laser performances are also investigated in detail. Single longitudinal mode laser outputs with single polarization are achieved in these two-phase-shift DFB-FLs.

The 4-cm-long DFB-FLs are written in the 5-cm-long photosensitive erbium-doped fiber (EDF) that has peak absorption of 8 dB/m at 1530 nm. For each DFB-FL, the EDF is spliced to the passive matching pigtail fiber (Nufern 980Hp) at both the ends. The grating is written by scanning 244 nm frequency-doubled harmonic argon ion continuous wave laser across the phase mask and fiber. Then, the polarization-dependent grating is generated by vertically polarized UV laser scanning. Figures 1 and 2 show the DFB-FL configuration and the fabrication setup diagram, respectively. The phase mask is mounted on a piezoelectric transducer stage (PI, P-752.11c) with nanometer resolution. The phase shift is introduced by a simple displacement of the phase mask to fiber during the beam scanning.

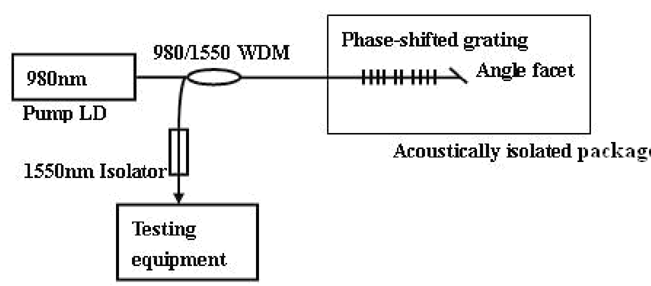

Fig. 1. Configuration diagram of DFB-FL.

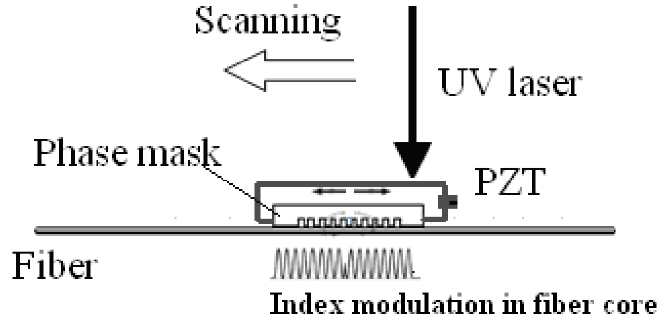

Fig. 2. Phase-shift grating fabrication setup diagram.

Table 1. Structural Parameters of the DFB-FLs

Code	Length (mm)	ΔN	PS	PP
DFB-FL1	40	1.3×10^{-4}	PS1 = PS2 = $\pi/2$	PP1 = 0.45 L, PP2 = 0.55 L
DFB-FL2	40	1.3×10^{-4}	PS1 = PS2 = $\pi/2$	PP1 = 0.39 L, PP2 = 0.49 L
DFB-FL3	40	1.3×10^{-4}	PS1 = PS2 = $\pi/2$	PP1 = 0.35 L, PP2 = 0.45 L

The displacement of the phase mask for an accurate π phase shift is a quarter of the phase mask period. For multiple phase shifts, multiple displacements are necessary at specific phase-shift position of the grating.

To meet the phase condition in the DFB-FL cavity with two phase shifts, the phase shift values are chosen as $\pi/2$ for each phase shift. Specific parameters including the structural and phase-shift parameters of the DFB-FLs are listed in Table 1. In Table 1, ΔN denotes the ac index modulation in the grating, PS denotes phase shift, PP denotes phase-shift position and L denotes the length of DFB-FL. Figure 3 shows the simulated grating spectra for comparison.

It is observed that the simulated transmission spectra of these three DFB-FL gratings are nearly same except for some differences in side bands. There is only one narrow transmission slit with high transmittance in the main Bragg reflection band, which means that only one longitudinal mode can oscillate in these DFB-FL cavities. Figure 4 shows the experimental grating

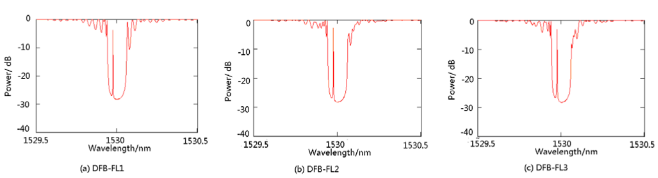

Fig. 3. Simulated transmission spectra of the presented DFB-FLs.

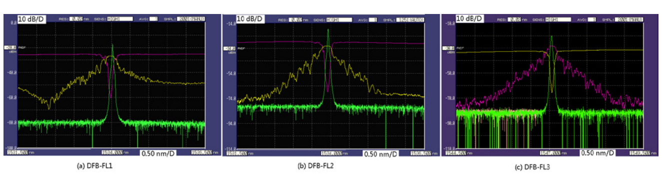

Fig. 4. Experimental grating spectra and laser spectra of the presented DFB-FLs measured with optical spectrum analyzer of 0.02 nm resolution. Green line: laser; Yellow: reflection; Purple: transmission

spectra and laser spectra. Although no obvious transmission slit can be distinguished, the single-wavelength laser spectra are observed. The single-polarization longitudinal mode operation is further verified by the polarization measurement and spectra measurement with high resolution (Apex 2040a, 0.16 pm resolution; Fig. 5).

Other laser performance tests, such as relative intensity noise (RIN), linewidth, pump threshold, and slope efficiency, are carried out. Results are listed in Table 2, where P_{th} denotes the pump threshold, P_b denotes the backward output power, P_f denotes the forward output power, and 1P denotes single-polarization single longitudinal mode. No obvious differences in the laser performances can be observed in the fabricated DFB-FLs. The spectral linewidth is measured by self-homodyne method with 30 km delayed fiber line and fitted with Lorentzian function. The degree of polarization (DOP) is measured with polarization analyzer (Agilent Inc., Model N7788B). All the measurements were performed under 980 nm pump LD and the RIN and linewidth parameters are the tested values under 100 mW pump power. The RIN listed here is the peak value at the relaxation oscillation frequency. For the symmetrical two-phase-shift DFB-FL, i.e. DFB-FL1, the output powers from both the ends are nearly equal. While for the other two DFB-FLs with asymmetrical phase-shift locations, the output powers from both the ends differ significantly and the ratio of backward-to-forward

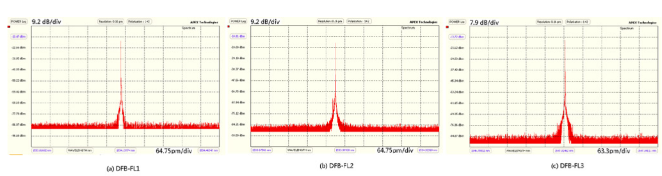

Fig. 5. Laser spectra measured with high-resolution (0.16 pm) optical spectrum analyzer.

Table 2. Laser characterization of the presented DFB-FLs with two phase shifts

Code	P_{th} (mW)	Slope efficiency	P_b/P_f	RIN (dB/Hz)	Linewidth (Hz)	DOP	Mode
DFB-FL1	<1	0.13%	1.5	–80	6k	1	1P
DFB-FL2	<1	0.14%	>200	–87	8k	1	1P
DFB-FL3	<1	0.13%	>100	–75	5k	1	1P

power exceeds 100, which is very useful and meaningful in applications.

In our experiments, the two phase shifts are assigned relatively close to each other, where the space gap is only 0.1 L and the total phase shift is equal to π. This design is similar to the DFB-FL with a single π phase shift, but reduces SHB effect to some extent. Indeed, multiple wavelength laser can be excited in other DFB-FLs with multiple phase shifts[15,16]. Hence, for better performance by further reduction of SHB in DFB-FL, the optimization design is required in the future work. With this experiment, it is also proved that the fabrication setup to generate phase shift and make grating is effective in the complicated grating experiment.

In conclusion, in the structure design, the space gap between the phase shifts is 0.1 L and the total phase shift is equal to π. The DFB-FLs with two phase shifts, which are located at different positions, are fabricated. Both symmetrical and asymmetrical outputs are obtained in different phase-shift configurations. The singe-polarization single longitudinal mode operation is observed in these DFB-FLs. It is proved that the single-polarization longitudinal mode laser with reduced SHB in cavity is obtained in the two-phase-shift DFB-FLs.

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