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Novel Raman Fiber Laser and Fiber-Optic Sensors Using Multi-Channel Fiber Gratings

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The transmission characteristics of multi-channel long period fiber gratings (LPFGs) in terms of the physical parameters like the separation distance, grating length and number of gratings will be discussed. Their transmission characteristics such as channel spacing, number of channels, loss peak depth, and channel bandwidth can be easily controlled by physical parameters. Based on the experimental results, their applications to optical multiwavelength Raman lasers and optical sensors will be investigated. A multiwavelength Raman fiber ring laser with 9 WDM channels with 100 GHz spacing and 19 channels with 50 GHz spacing using tunable multi-channel LPFGs will be experimentally demonstrated. The fiber-optic sensing applications with high resolution and sensitivity based on multi-channel LPFGs will be also presented.

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I. INTRODUCTION

Fiber gratings have drawn significant attention in wavelength division multiplexing (WDM) communication systems and optical fiber sensors due to their wavelength-selective nature. LPFGs, for example, are used as band rejection filters [1], gain flattening filters for erbium doped fiber amplifier (EDFA) [1], and fiber-optic sensors. [2,3]

It has been recently reported that several LPFGs can be cascaded in series to form comb filters, or multi-channel LPFGs, which can be used for fiber-based WDM filters. [4,5] There has been considerable effort to utilize these features for various applications, and it is often necessary to control the spectral characteristics, e.g., the spectral spacing between adjacent channels in multi-channel LPFGs.

In this paper, we will discuss the relationship between the physical parameters (like the separation distance, grating length and number of gratings) and the transmission characteristics of multi-channel LPFGs, i.e., spectral channel spacing, number of channels, loss peak depth, and channel bandwidth. In particular, theoretical analysis and experimental measurement results will be presented that establish the relationship between the physical parameters of multi-channel LPFGs and the transmission characteristics. Based on the experimental results, the application of multi-channel LPFGs to tunable multiwavelength Raman fiber ring lasers and optical sensors with high resolution and high sensitivity will be experimentally investigated. The results presented in this work can be used to control the transmission characteristics of multi-channel LPFGs and will be extremely useful for applications in WDM filters, multiwavelength fiber lasers, and physical/mechanical sensors.

II. TRANSMISSION CHARACTERISTICS OF MULTI-CHANNEL LPFGS

The principle of multi-channel LPFGs is based on the interference between the core mode and cladding modes. As shown in Fig. 1 (a), the first LPFG splits

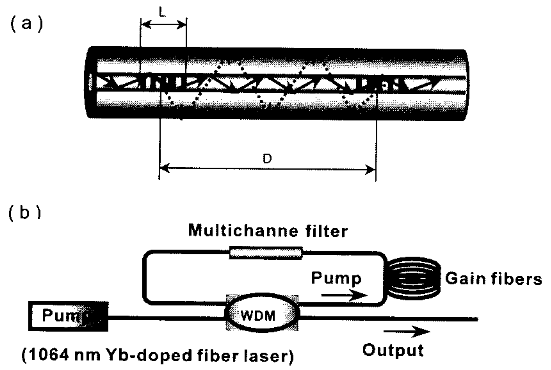

FIG. 1. (a) The schematic of the interference between the core and cladding modes generated by two LPFGs, and (b) experimental setup of multiwavelength Raman fiber ring laser using multi-channel LPFGs.

the power of the fundamental HE11 core mode between the core and cladding modes, and in the grating-free region between the two LPFGs, the core and cladding modes propagate simultaneously. The two modes then interact in the second LPFG and generate the spectral fringe patterns.

Based on the co-directional coupled mode theory, the modal amplitudes of the core and cladding modes in cascaded LPFGs can be easily analyzed. [5] Once the transfer matrix of a unit composed of an LPFG and a grating-free region is obtained, the modal amplitudes of the core and cladding modes after N such units, or N-cascaded LPFGs, can be obtained by calculating the N-th power of the matrix. If the center-to-center separation distance between the gratings is D and if the grating length is L, the length of the grating-free region is $D-L$, and the modal amplitudes of the core and cladding mode after passing through N identical units can be written in matrix form as

$$\begin{pmatrix} a_{co} \\ a_{cl} \end{pmatrix}_{out} = e^{i(\beta_{co}+\beta_{cl})ND/2} A^N \begin{pmatrix} a_{co} \\ a_{cl} \end{pmatrix}_{in} \quad (1)$$

where

$$A = \begin{pmatrix} e^{i\phi/2}(\cos sL + i\dfrac{\Delta\beta}{2s}\sin sL) & e^{i\phi/2}\dfrac{i\kappa}{s}\sin sL \\ e^{-i\phi/2}\dfrac{i\kappa^*}{s}\sin sL & e^{-i\phi/2}(\cos sL - i\dfrac{\Delta\beta}{2s}\sin sL) \end{pmatrix} \quad (2)$$

a_{co} and a_{cl} represent the modal amplitudes of the core and cladding modes, respectively, while β_{co} and β_{cl} are the corresponding propagation constants. A is the transfer matrix of a unit that comprises an LPFG and a grating free region, and it can be expressed in terms of the coupling constant κ and the grating period Λ.

LPFGs were fabricated with KrF excimer laser and an amplitude mask. The grating period, laser repetition rate, and energy per pulse were 400 μm, 30 Hz, and 176 mJ/pulse, respectively. The grating length L was varied. Versatile multi-channel LPFGs were then fabricated by cascading LPFGs in series with varying separation distance D and number of gratings N. The parameters and transmission characteristics of the multi-channel LPFGs used in this work are shown in Table 1. Only the loss peaks with the depth larger than -3dB were considered for counting the number of channels N_{ch}.

TABLE 1. Parameters and characteristics of multi-channel LPFGs. L: grating length, D: separation distance, N: number of gratings, S: channel spacing, B: bandwidth, N_{ch}: number of channels.

Fig	L [cm]	S.D [cm]	# of Gra.	Experiments S [nm]	Experiments B [nm]	Experiments #of Ch.	Simulations S [nm]	Simulations B [nm]	Simulations #of Ch.
		10		3.44		5	3.56		5
1	2	20	2	1.87		11	1.91		11
		30		1.21		17	1.22		17
		40		0.87		21	0.89		21
2	2	10	2	3.44	3.44	5	3.56	3.56	5
			3		2.23			2.22	
			2		3.44			3.5	
			2		3.44			3.5	
3	1	10	3	3.44	2.23	12	3.56	2.33	11
			4		1.38			1.51	
			5		1.11			1.23	

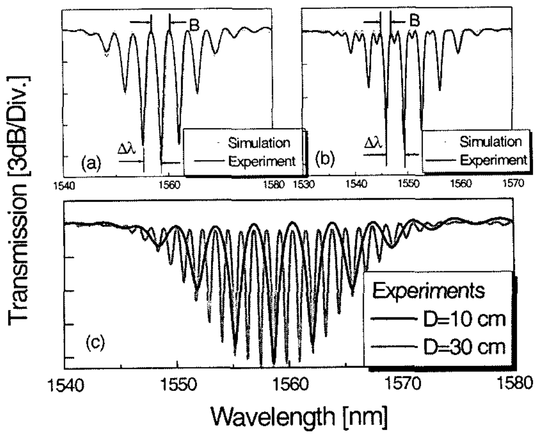

FIG. 2. (a) Theoretical and experimental results for the transmission spectra of pair LPFGs (N = 2) with L = 2 cm, D = 10 cm, (b) Theoretical and experimental results for the transmission spectra of multiple-cascaded LPFGs with L = 2 cm, N = 3, D = 10 cm, and (c) the effect of the separation distance D on the transmission characteristics of pair LPFGs (N = 2) with D = 10 cm and 30 cm.

Figs. 2(a), (b), and (c) show the theoretical and experimental results of the transmission spectra of pair LPFGs with L = 2 cm and D = 10 cm, multiple-cascaded LPFGs with N = 3, and pair LPFGs (N = 2) with separation distance D of 10 cm and 30 cm. Fig. 3 shows the transmission characteristics of multiple-cascaded LPFGs with N = 5, L = 1 cm, and D = 10 cm. Fig. 4 shows the effect of the number of gratings N on the transmission characteristics of multiple-cascaded LPFGs with L = 2 cm and D = 10 cm. The slight discrepancy between the numerical simulation and measurement result is due to the dispersion effect, which caused the error in the center wavelength and coupling strength. The result shows that the channel spacing decreases as D

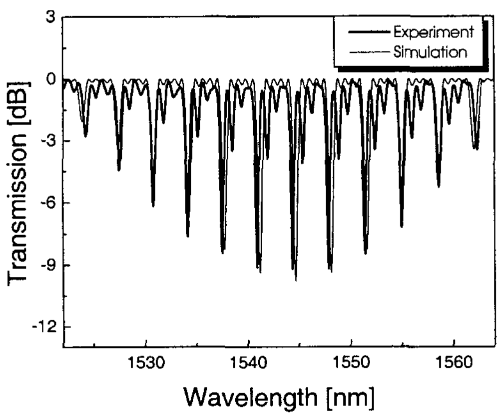

FIG. 3. Theoretical and experimental results for the transmission spectra of multiple-cascaded LPFGs with L = 1 cm, N = 5, D = 10 cm.

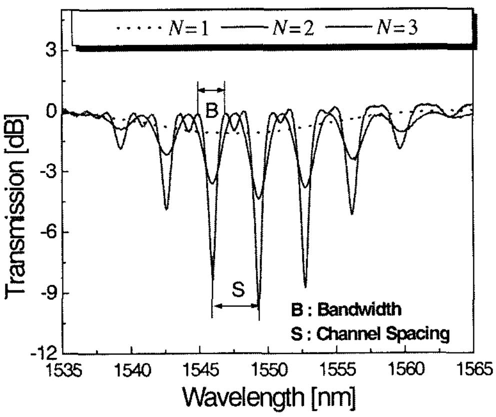

FIG. 4. The effect of the number of gratings N on the transmission characteristics of multiple-cascaded LPFGs with L = 2 cm and D = 10 cm.

increases. The bandwidth decreases as N increases and the loss peak depth also increases with N, while the channel spacing is the same for both cases of N = 2 and N = 3.

III. TUNABLE MULTIWAVELENGTH RAMAN FIBER RING LASER USING MULTI-CHANNEL LPFGS

Multiwavelength laser sources have gained a lot of attention in recent years due to the demand for the high transmission capacity in wavelength division multiplexing (WDM) systems. [6] We tried to apply the multi-channel LPFGs to the multiwavelength Raman fiber ring laser. The multiwavelength Raman fiber lasers based on multichannel LPFGs have many advantages such as low cost, low insertion loss, simple configuration, ease to expand their operation wavelength and bandwidth, and the stable operation at room temperature compared with the multiwavelength Er-doped fiber lasers. [6] Since multichannel filters based LPFGs have high flexibility and tunability, the tunable multiwavelength fiber lasers can be easily fabricated. Therefore, they are very useful for applications in the high capaicty WDM systems. We also extended the operation bandwidth of multiwavelength Raman fiber lasers to E- and L-bands compared with that of the previous report [7], which was operated in C-band.

Fig. 1 (b) shows the experimental setup of the multiwavelength Raman fiber ring laser based on cascaded LPFGs. The ring cavity was composed of a WDM coupler, 4 km Raman gain fibers and a multi-channel filter based on cascaded LPFGs. We used high dispersion-

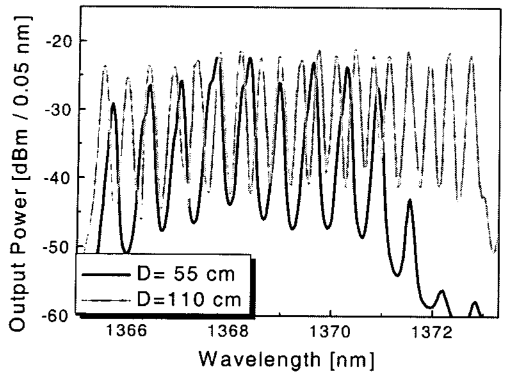

FIG. 5. Experimental results of multiwavelength output spectra using 4 km DSF for different pumping powers P_p: (a) $P_p = 5$ W, $D = 55$ cm, $\Delta\lambda = 0.66$ nm for 100 GHz and (b) $P_p = 5.6$ W, $D = 110$ cm, $\Delta\lambda = 0.33$ nm for 50 GHz.

shifted fiber (DSF) as the Raman gain fibers and measured the output characteristics for comparison purposes. The 1064 nm Yb-doped fiber laser was used as a pump source. Fig. 5 shows the multiwavelength output spectra of the 5th Raman Stokes wave using 4 km DSF as a gain medium with the pumping power around 5 W. For the grating separation distance of 55 cm, the wavelength channel spacing was 100 GHz (~ 0.66 nm) in the E-band. There are 9 WDM channels with extinction ratio higher than 20 dB in this case. For the separation distance of 110 cm, the number of channels increases to 19 WDM channels since the number of channels of the multi-channel filter increases with the increase in the grating separation distance. The wavelength spacing was 50 GHz (~ 0.33 nm) in this case. The multiwavelength operation based on cascaded LPFGs can be used for both this specific Raman Stokes wave and all Raman Stokes waves.

IV. SENSING APPLICATION OF MULTI-CHANNEL LPFGS

We applied the multi-channel LPFGs with $L = 2$ and $D = 10$ cm to torsion sensors. Recently, the application of LPFGs to torsion sensors has been of interest. [3] However, it requires specially designed grating structure like corrugated gratings, which have the drawbacks of fabrication difficulty, high background loss, and degradation of mechanical strength. Torsion sensors based on cascaded LPFGs have a lot of advantages like simple fabrication process, no background loss, and no degradation of mechanical strength. Additionally, since the resonant wavelength is not changed with the variation of torsion, it is very useful for practical applications to fiber optic sensors.

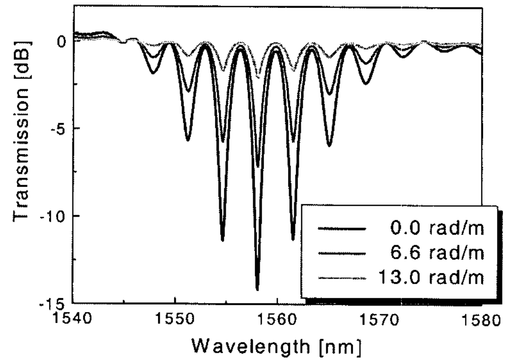

FIG. 6. Experimental results of transmission characteristics of an LPFG pair with the torsion change.

Figs. 6 and 7 show transmission characteristics of multi-channel LPFGs with the torsion change. The cladding modes are more susceptible to the changes in the environment, and therefore, loss of the power carried by the cladding modes increases as the fiber is twisted, which results in decrease of the center peak depth. The twisting of the fiber changes the field profiles of the core mode and cladding modes, which in turn results in reduction of the coupling coefficient, κ, and decrease of the resonant peak depth. The resonant wavelength was not changed. The linear fitting of the center peak depth (T_p) with respect to the variation of the twist ratio (T) along the fiber in the range from 3 to 11 rad/m gives

$$T_p = -17.3 + 1.5T \tag{3}$$

This result can also be applied to the amplitude modulation of multi-channel filters.

We also measured the sensitivity of the LPFG pair to the ambient index changes as shown in Fig. 8. Shift of the resonant fringe with the ambient index change is shown in the inset. Since the effective indices and

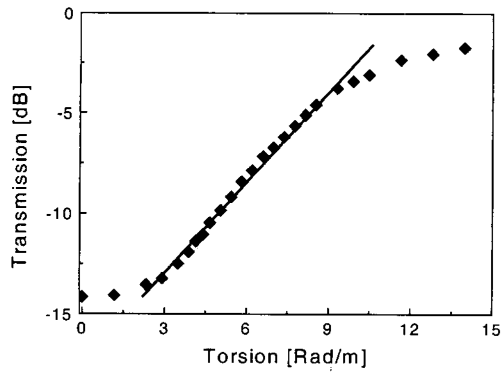

FIG. 7. Variation of the maximum peak depth of an LPFG pair with the torsion change.

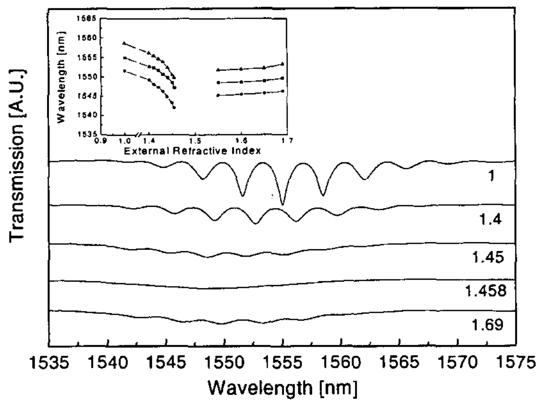

FIG. 8. Changes of the transmission characteristics of an LPFG pair due to the surrounding refractive index change. The resonant fringe shift with the ambient index change is shown in the inset.

the field profiles of the cladding modes change in response to the ambient index change in the normal fiber region, the contrast of the interference fringe pattern is degraded and the peak wavelength shifts occur. If the ambient index is similar to that of the effective index of the cladding mode, the interference between the core and cladding modes in the second grating disappears altogether. As the ambient index is further increased, the interference pattern appears again due to the modes that propagate in the surrounding region. Since the transmission characteristics of the LPFG pair heavily depend on the ambient index change, the LPFG pair will be useful for oil and chemical sensors.

V. CONCLUSION

The transmission characteristics of multi-channel LPFGs in terms of physical parameters like the separation distance, grating length and number of gratings were theoretically and experimentally investigated. These parameters could control the transmission properties of multi-channel LPFGs such as channel spacing, number of channels, loss peak depth, and channel bandwidth. To summarize the results, the channel spacing decreased as the separation distance between the LPFGs increased, the number of channels decreased as the grating length increased, and the loss peak depth increased as the number of gratings increased. The numerical simulation based on co-directional coupled mode theory and the measurement results showed good agreement.

We discussed the various applications of multi-channel LPFGs to multiwavelength fiber lasers and fiber-optic sensors. The multiwavelength Raman fiber ring lasers with 9 WDM channels with 100 GHz spacing and 19 channels with 50 GHz spacing using tunable multi-channel LPFGs were fabricated. We presented the fiber-optic sensing applications of multi-channel LPFGs to torsion and chemical sensing. Due to the fine interference fringe patterns and their narrow bandwidth in the transmission spectrum, the sensing devices based on the LPFG pair provide high resolution and sensitivity compared with a single LPFG.

The results can be utilized to control the transmission characteristics of multi-channel LPFGs for applications to WDM communication systems and optical fiber sensors.

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