Development of Optical Fiber Gratings for WDM Systems

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ABSTRACT Full-scale implementation of wavelength-division multiplexing (WDM) has focused attention on optical fiber gratings, capable of multiplexing/demultiplexing of multiple wavelengths. Furukawa Electric has carried out basic R & D on optical fiber gratings, developing products for WDM systems and a variety of other applications. This paper introduces the basic theory of optical fiber gratings and describes manufacturing techniques. It also summarizes developmental results with emphasis on gratings for WDM system applications.

1. INTRODUCTION

Optical fiber gratings make use of the photo-refractive effect discovered by Hill et al. in 1978, whereby the refractive index of an optical fiber is increased by exposure to ultraviolet light.[1] At that time, the grating depended on interference between the forward-propagating wave incident on the fiber and the backward-propagating wave resulting from reflection at the end face of the fiber. Thus the Bragg wavelength depended on the wavelength of the laser light input to the fiber, making it impossible to form a grating of the desired wavelengths. Later, however, a method was proposed by Meltz et al. whereby the fiber was irradiated laterally with UV light, producing in the core a grating of the desired period.[2] It further became possible, by treating the fiber with high-pressure hydrogen, to increase its photosensitivity,[3] accelerating R&D to the point where commercially viable products are now available.

Over the past few years, the Internet has led the rapid increase in demand for fiber-optic communications, and major strides have been made in WDM systems to increase the transmission capacity of existing lines. In this area, fiber gratings are being used in filtering devices for multiplexing/demultiplexing in WDM systems, gain equalizers for Erbium-doped fiber amplifiers (EDFAs), and in the external cavity lasers, used to stabilize light-source wavelength.

This paper describes the principle of the optical fiber grating and techniques for its manufacture, and introduces some products applying fiber gratings in WDM systems.

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2. PRINCIPLE OF THE OPTICAL FIBER GRATING

2.1 Overview

The optical fiber grating is a device that creates a periodic perturbation in the refractive index of the fiber core, reflecting only the specific wavelength corresponding to that period.

This periodic perturbation in the refractive index is brought about by forming an interference fringe on the fiber by means of lateral irradiation with UV light, and by writing that pattern in the fiber by the photo-refractive effect.

There are two methods that are commonly used to produce the interference fringe. The first is known as the holographic method (see Figure 1), in which UV light is passed through a beam splitter and reflected by a mirror to form an interference fringe at the point of intersection. A grating of the required characteristics can be obtained by making minute adjustments to the angle of the mirror, but this method requires a light source of high coherency and is easily influenced by the vibration of the optics, etc.

The other method is known as the phase-mask method, in which fine slits are made in a phase mask mounted on a silica substrate by exposing it to an electron beam or the like. For light passing through the phase mask (see Figure 2), the 0-order light traveling straight ahead is almost entirely suppressed, so that the interference produced by the ±1-order light can be formed on the fiber. The relation-

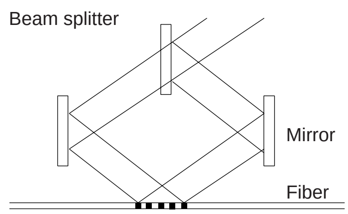

Figure 1 Holographic method

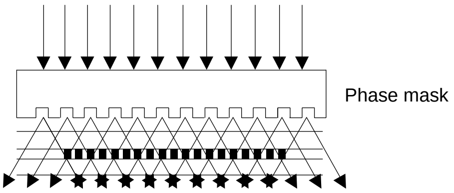

Figure 2 Phase-mask method

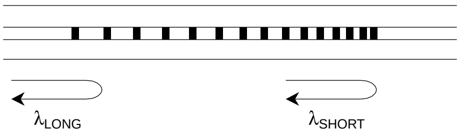

Figure 3 Principle of dispersion-compensating grating

ship between the period of the phase mask Λ_{MASK} and the period of the fiber grating Λ_{FBG} may be shown as

$$\Lambda_{MASK} = 2\Lambda_{FBG} \quad ...(1)$$

Thus when it comes to producing fiber gratings of differing wavelengths, this method has the disadvantage of requiring several masks according to the period of the grating, making for higher cost than with the holographic method. However it achieves more stable characteristics and is better suited to mass production, and is therefore the method generally adopted for the manufacture of optical fiber gratings.

The optical characteristics of fiber gratings are determined by three parameters: the magnitude of the perturbation in the refractive index, the period of the grating, and its length. The magnitude of refractive index perturbation and grating length in the main greatly influence reflectance and bandwidth. The period of the grating, on the other hand, determines the center wavelength, and it is also possible, by varying its magnitude in the longitudinal direction, to realize various types of gratings.

Gratings having a period that is constant in the longitudinal direction are referred to as "uniform", and they generally have a steep wavelength characteristic with sharp peaks. Depending on grating length, bandwidths of 0.1 nm or less are possible, and such devices are widely used for add-drop and narrow-band WDM applications. The center wavelength may be represented by

$$\lambda_B = 2n\Lambda \quad ...(2)$$

where: λ_B is the Bragg wavelength.

Since the effective refractive index n of the mode and the grating period Λ vary with respect to temperature and distortion, monitoring the center wavelength can provide a temperature and distortion sensor.

Gratings with a period that varies in the longitudinal direction, on the other hand, are referred to as "chirped" gratings. Since the reflected wavelength is represented in Equation (2), a continuous change in period appears as a continuous change in reflected wavelength, and a broadband waveform can be obtained. Chirped gratings have a wide range of applications including band rejection filters, and since their reflection point differs according to the wavelength (see Figure 3) they could also serve as dispersion compensators. [4)]

2.2 The Photo-reactive Effect

As was stated above, an optical fiber grating is a device in which an area with an increased refractive index is formed periodically in the fiber core. This higher index can be achieved easily, merely by irradiating the fiber with UV light, but the mechanism by which this occurs is still not fully understood. Several models have been proposed, however, and it may well be that they interact. Here we propose to introduce the Kramers-Kronig model as the primary one among these interacting mechanisms. [5)]

The spectrum of germanium-doped fiber has an absorption band at around 240 nm, so that the nearby area is bleached by the UV irradiation, and instead of this an absorption band, which is thought to be due to the GeE' center, is produced on the shorter-wavelength side. It is by means of this change in the absorption spectrum that the Kramers-Kronig relationship explains the increase in the refractive index.

Further, because the amount of perturbation of the refractive index increases during the manufacture of optical fiber gratings, a method is frequently adopted whereby hydrogen is added to the fiber in high concentrations prior to UV irradiation. The role of the hydrogen has been insufficiently explored, but it is thought to contribute to the activation of the reaction and the fixation of defects.

2.3 Mode Coupling Theory

If we let A(z) be the amplitude of the forward-propagating wave and B(z) be the amplitude of the backward-propagating wave, the electrical field distribution E(z) in the fiber may be represented by

$$E(z) = A(z)\exp(-i\beta z) + B(z)\exp(i\beta z) \quad ...(3)$$

A(z) and B(z) will also satisfy the mode coupling equation

$$\frac{dA}{dz} = -i\kappa B\exp(2i\delta z)$$
$$\frac{dB}{dz} = i\kappa A\exp(-2i\delta z) \quad ...(4)$$

where κ is a coupling coefficient and $\delta = \beta - \pi/\Lambda$.

Solving Equation (4) for the vicinity of the peak, we then have

$$\begin{pmatrix} A(z)\exp(-i\delta z) \\ B(z)\exp(i\delta z) \end{pmatrix} = M \begin{pmatrix} A(0) \\ B(0) \end{pmatrix} \quad ...(5)$$

$$M = \begin{pmatrix} \cosh(\gamma z) - i\frac{\delta}{\gamma}\sinh(\gamma z) & -i\frac{\kappa}{\gamma}\sinh(\gamma z) \\ i\frac{\kappa}{\gamma}\sinh(\gamma z) & \cosh(\gamma z) + i\frac{\delta}{\gamma}\sinh(\gamma z) \end{pmatrix} \quad ...(6)$$

where: $\gamma = \sqrt{\kappa^2 - \delta^2}$

The reflectance *R* of a fiber grating with a length of *L* can be obtained by substituting z = *L* and *B*(*L*) = 0 in Equations (5) and (6), as

$$R=\frac{\kappa^2\sinh^2(\gamma L)}{\gamma^2+\kappa^2\sinh^2(\gamma L)} \quad \ldots(7)$$

Then by substituting $\gamma=\kappa$ in Equation (7), reflectance at peak wavelength becomes

$$R=\tanh^2(\kappa L) \quad \ldots(8)$$

3. OPTICAL FIBER GRATINGS FOR OADMs

WDM communication systems require an optical add-drop multiplexer (OADM) to add to (or drop from) the line a specified signal wavelength. Since the optical fiber grating is a device with a steep wavelength characteristic and good wavelength selectivity, it may be considered as applicable to OADM systems. Figure 4 shows an example in combination with a circulator. The reflected wavelength λ_1 of the grating is dropped from the IN port to the DROP port and signal λ_1 from the ADD port is reflected by the grating and added to the OUT port line.

There are two characteristics that may be adduced as essential for an optical fiber grating for OADM applications: 1) a steep spectrum without ripples in the transmission and reflection characteristics; and 2) lower loss in the transmission band.

When the refractive index perturbation of the grating is uniform in the longitudinal direction of the fiber (see Figure 5(a)), the reflection spectrum has, on either side of the main peak, a plurality of peaks known as side-lobes, which can be suppressed (Figure 5(b)) by a technique known as apodization, in which refractive index perturbation is reduced on both sides of the grating.[6] Figures 6 shows calculated values for the reflection spectrum when not apodized, and Figure 7 shows analogous values when the Gaussian distribution is apodized. Apodization can be done relatively easily by varying the amount of UV irradiation either mechanically or optically while the grating is being written.

A further problem is excessive loss on the shorter wavelength side of the main peak in the transmission spectrum. Figure 8 shows the transmission spectrum when a grating is written in an ordinary single-mode fiber. This is due to coupling from the waveguide mode to the backward-propagating cladding mode. This may be overcome by suppressing the coupling itself and by shifting the region in which the excessive loss occurs outside the waveband being used. In either case it is achieved by modifying the profile of the fiber. As methods that suppresses the cou-

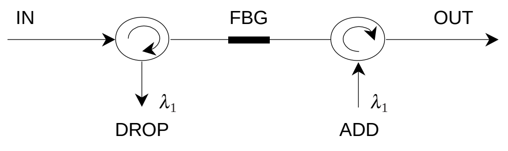

Figure 4 Schematic of OADM with fiber Bragg grating

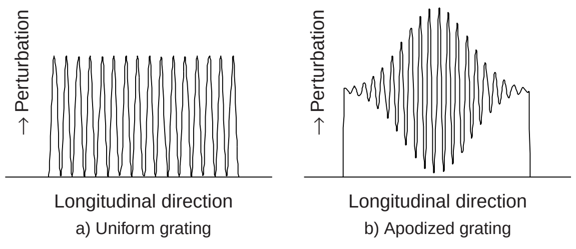

Figure 5 Refractive index perturbation of uniform and apodized gratings

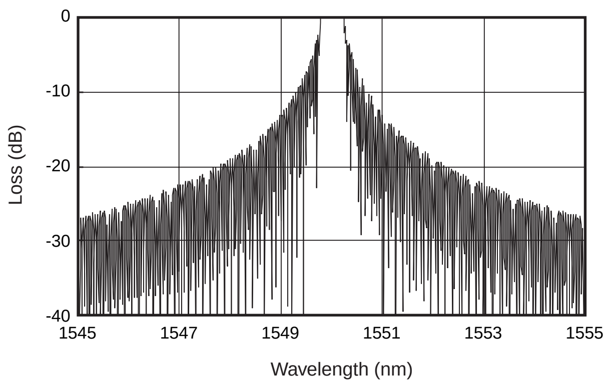

Figure 6 Reflection spectrum of uniform grating (calculated)

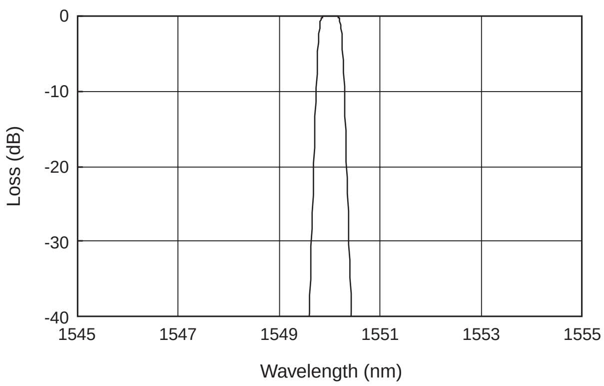

Figure 7 Reflection spectrum of apodized grating (calculated)

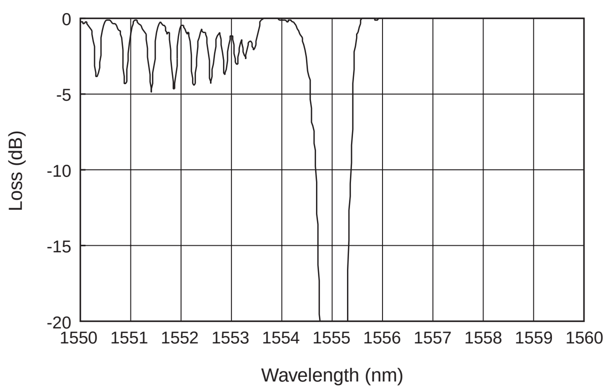

Figure 8 Transmission spectrum of fiber grating written in a single-mode fiber

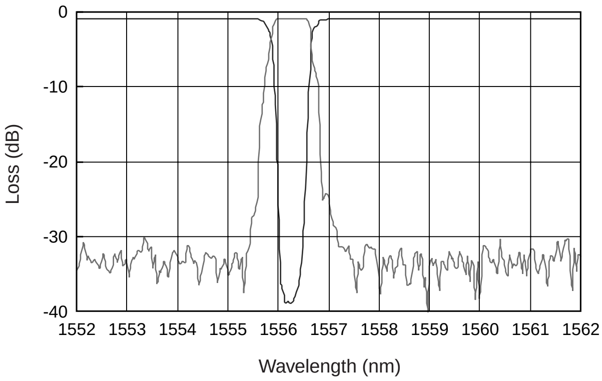

Figure 9 Transmission and reflection spectra of fiber grating written in a high-NA fiber

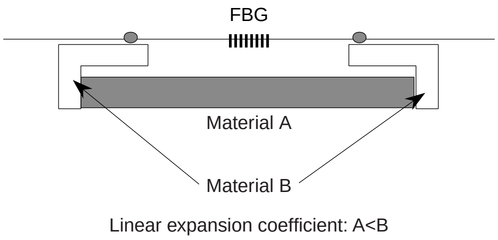

Figure 10 Temperature-compensated package composed of two materials such that the coefficient of linear expansion of A is less than that of B

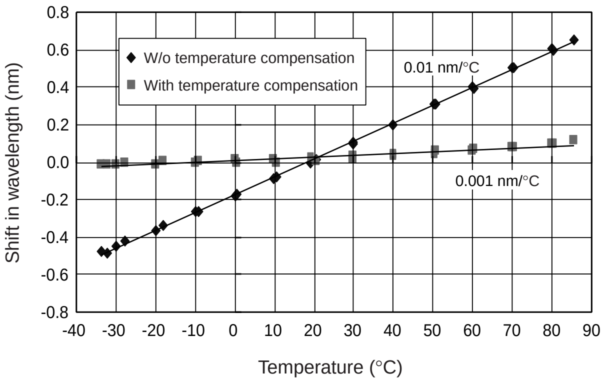

Figure 11 Temperature dependence of center wavelength of temperature-compensated package

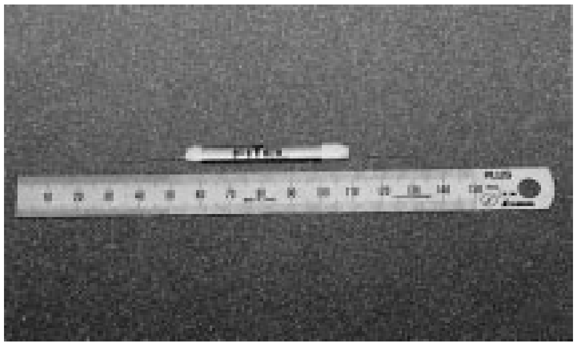

Photo 1 Temperature-compensated fiber grating

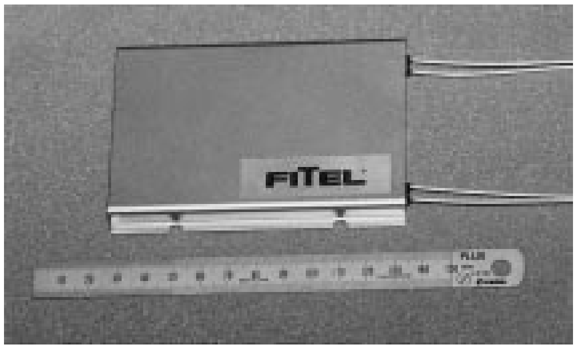

Photo 2 OADM module

pling itself, a Ge co-doped cladding fiber [7] and a W-shaped index fiber [8] have been proposed. To shift the peak outside the waveband used, a high-NA fiber is effective. [9] By using a high-NA fiber of proprietary design, we are producing gratings that are unaffected by the cladding mode 12 nm and more from the main peak.

Figure 9 shows transmission and reflection spectra when a high-NA fiber was used. A KrF excimer laser was used as the UV light source, and the phase-mask method of manufacture was used. There was no excessive loss in the transmission band, and gratings with steep wavelength characteristics were obtained.

Another important point in relation to WDM systems, given the small intervals between wavelengths, is wavelength control technology. With ordinary fiber gratings, the change in center wavelength due to temperature amounts to about 0.01 nm/°C. Any temperature-caused divergence of center wavelength from grid wavelength will lead to degradation of transmission characteristics, so that the center wavelength of the grating should remain fixed at the grid wavelength irrespective of temperature.

The temperature-dependence of the center wavelength may be attributed to the fact that n and Λ in Equation (2) increase with rises in temperature. The temperature-dependence of n is inherent in the material of which the fiber is made and is difficult to change, but the temperature-dependence of Λ is comparatively easily suppressed. Thus if it has an inverse relationship to temperature, it can cancel out the increase in n to provide a constant center wavelength.

To achieve such an inverse relationship, we may use a package made of a material with a negative coefficient of linear expansion [10] or, as shown in Figure 10, of materials with different coefficients. [11]

Figure 11 shows the temperature-dependence of the center wavelength for a grating having a package made of two different materials. The temperature-dependence is 0.001 nm/°C or less, a variation that can be ignored at the temperature range in which OADMs are used.

Photo 1 shows a fiber grating having a temperature-compensated package, and Photo 2 shows an OADM module combining a circulator. The module measures only 108 x 80 x 8.5 mm, making it extremely compact and convenient.

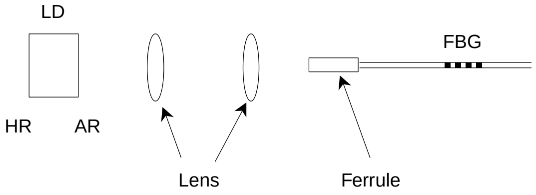

Figure 12 Structure of a pumping laser diode with fiber grating

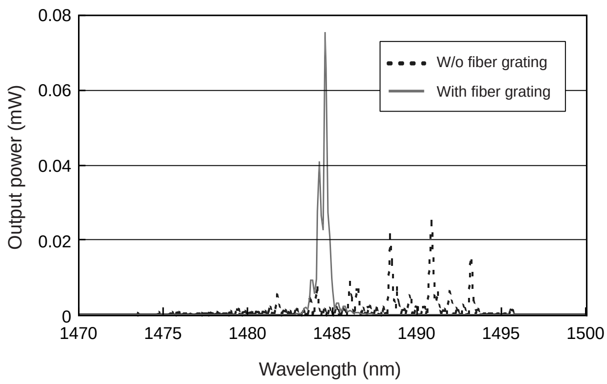

Figure 13 Output spectra of laser diodes with and without fiber grating

4. FIBER GRATINGS FOR LASER WAVE-LENGTH STABILIZATION

The pumping light source for EDFAs is provided by 1.48-µm and 0.98-µm laser diodes. To achieve higher EDFA output requires higher power from the pumping diode, together with the use of wavelength-division or polarization multiplexing.

To achieve wavelength-division multiplexing, it is essential that the peak wavelength of the pumping diode be stable with respect to the ambient conditions of use, and that the spectral band be narrowed.

Ordinary diodes lase by means of a Fabry-Perot resonator using the chip end face, so that other modes lase simultaneously, leading to broadening of the spectrum. In addition, perturbation of the refractive index of the activated region is produced by changes in injection current and temperature, as a result of which the effective change in cavity length is manifested as a change in peak wavelength of the laser.

If a fiber grating having a reflectivity of several percent is arranged outside the pumping diode, lasing will occur using the grating as an external cavity. In this case, lasing will be due primarily to the fiber grating, and the peak wavelength will accord almost exactly with the center wavelength of the fiber grating.

Since the temperature-dependent variation in the center wavelength of the fiber grating is extremely small relative to the variation in the peak wavelength referred to above, the peak wavelength of a laser with a fiber grating will be stable with respect to temperature. It is also possible to obtain a narrower laser spectrum by reducing the bandwidth of the fiber grating.

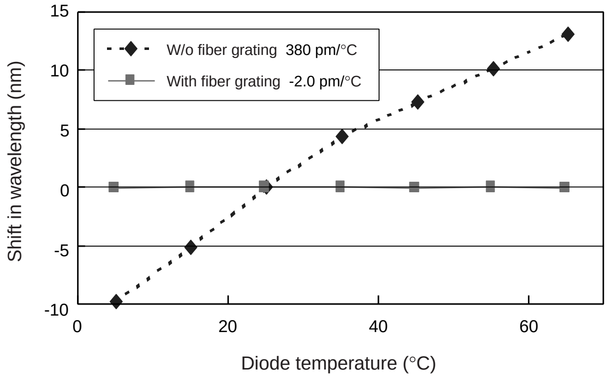

Figure 14 Temperature-dependence of peak wavelength of laser diodes with and without fiber grating

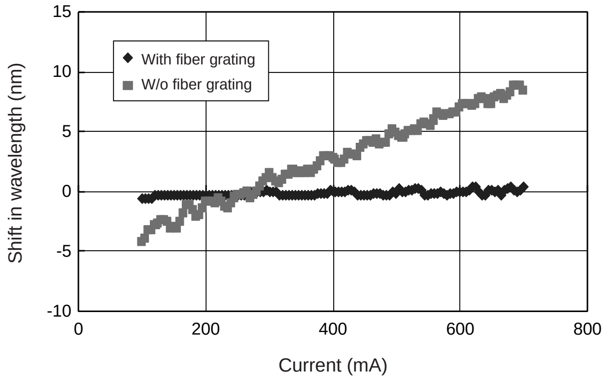

Figure 15 Current-dependence of peak wavelength of laser diodes with and without fiber grating

Figure 12 shows the structure of a pumping laser diode with a fiber grating. Due to the lenses at the antireflective coating side of the diode, part of the light coupled to the fiber is reflected by the fiber grating forming an external cavity with the highly reflective facet of the diode.

The fiber grating is produced by UV irradiation of a fiber that has been treated with high-pressure hydrogen using a KrF excimer laser. The area on which the grating is written is protected by a hard package or by recoating. If a package is used, careful attention to the structure and materials used can result in gratings of even higher temperature stability than those that are recoated.

Figure 13 shows the output spectrum of a 1.48-µm pumping laser diode with a fiber grating (solid line) and without a grating (dotted line). Whereas the diode without the grating has a broader output spectrum and a lower peak level, it can be seen that in the diode provided with a grating, output power is pulled in to the grating making for a narrower band and higher output power.

Figure 14 shows the diode temperature dependence of the peak wavelength of a 1.48-µm pumping laser diode with a fiber grating. Whereas for the diode without the grating the peak wavelength shifts to the longer side as diode temperature rises, there is virtually no influence of temperature on the diode with a grating.

Figure 15 shows the change in peak wavelength due to injection current. Here too it can be seen that in the diode with a grating, peak wavelength remains stable.

5. CONCLUSION

The results of a program to develop fiber gratings for OADM applications and for stabilizing the wavelength of pumping lasers in WDM systems has been reported.

The target wavelength characteristics for OADM gratings were achieved by optimization and apodization of the fiber. The use of temperature-compensated packages made it possible to develop optical fiber gratings for use in commercial OADM systems. We have also commercialized an extremely compact OADM module, combining a circulator and fiber grating.

By incorporating a fiber grating in a pumping laser diode, its effectiveness was confirmed, and pumping lasers with fiber grating have been produced on a commercial basis.

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