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Brief Communication

CW-Pumped Evanescent Amplification Based on Side-Polished Fiber with Heavily Er^{3+}-Doped Glass Overlay

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A novel diffractive-pumping scheme is proposed to improve the evanescent amplification using blazed fiber grating for the first time. We also investigate the cw-pumped evanescent amplification at 1.55 µm wavelength with the relative optical gain pumped at 1480 nm of around 2 dB based on side-polished fiber with the effective interaction length as long as 16 mm and with a heavily Er^{3+}-doped ($N_{Er^{3+}} > 1.19 \times 10^{21}$ ions/cm^3), low refractive index ($n_{1550} < 1.47$) glass overlay, which has no concentration quenching ($\tau_f = 9.0$ ms). [DOI: 10.1143/JJAP.45.6328]

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The major pumping schemes for fiber amplifiers and lasers can be distinguished into core-pumping,[1)] cladding-pumping,[2)] side-pumping,[3)] and evanescent-pumping.[4–7)] The core-pumping method was shown to have the best quantum efficiency while the cladding- and side-pumping are for high pump power delivering purposes. However, the problems of gain-robbing and noise-raising caused by the guided amplified spontaneous emission (ASE) in core are unavoidable. Though most of the ASE noise can be removed by filters, the residual noise having the same wavelength with signals is still guided to degrade the states of polarization of the output amplified signals. This would be disadvantageous for the fiber interferometry.

In contrast, optical fiber with the passive-core and active-cladding structure was shown to have low ASE noise[8)] based on evanescent-pumping. For evanescent-pumping, fiber amplifiers were successfully achieved based on side-polished fiber (SPF).[9,10)] Besides the low ASE noise, evanescent-pumping has another advantage in achieving optical amplification at any wavelength contingent on the gain medium on the SPF. This is quite difficult to realize for other above pumping schemes since many of the low phonon energy glasses are excellent host glass for e.g., Pr^{3+}, Nd^{3+}, Ho^{3+}, and Tm^{3+} ions but are not suitable to be drawn into fibers because the crystallization makes the intrinsic losses highly raised.[11)] By attaching the gain medium onto the SPF, the pump light excites the gain medium to give rise to stimulated emission for the incident signals via the exponential decay evanescent fields. The stimulated photons follow the direction of the reflected signals instead of the incident pump lights and are subsequently guided inside the core and propagate forward.[12)] The spontaneous emissions occur outside the SPF and escape away while only fractions of them satisfying the phase-matching condition can be coupled back to propagate in core and amplified, which makes the ASE naturally depressed. However, the evanescent-pumping is inefficient since the evanescent gain is highly relevant to the overlap between the local signal and pump beam intensity as well as their interaction length along the gain medium.[6)] Hence, previous works[9,10)] were not successful in cw-pumping. The inefficient evanescent-pumping was imputed to the short effective interaction length L_{eff} (1–2 mm)[9,10)] and poor overlap among the gain medium and evanescent fields of the signal and pump lights, ascribing to dispersive evanescent wave tunneling[13)] in which the index difference between the gain medium and SPF goes up when wavelength goes down. Consequently, the pump light is more tightly confined in core than the signals and its penetration of evanescent field is too weak to make the gain medium in sufficient population inversions. It is worthy noting that a heavily doped and heavily pumped gain medium is important to high gain efficiency and low noise figure.

In this work, a diffractive-pumping scheme is proposed to improve the evanescent amplification and the cw-pumped evanescent amplification is investigated based on a heavily Er^{3+}-doped fluorophosphates glass (EDFG) attached onto the SPF with long L_{eff}. A relative gain of around 2 dB at 1.55 µm wavelength is achieved and, to the best of our knowledge, this is the first time that a cw-pumped evanescent amplification using a laser glass and operating at communication wavelengths is successfully demonstrated. In our diffractive-pumping scheme, a 10° tilted fiber grating is inscribed in interaction region of the SPF to spatially separate the signal and pump lights, which can be efficiently diffracted toward the gain medium, as shown in Fig. 1, despite the highly dispersive evanescent wave tunneling between the SPF and gain medium.

For evanescent amplification, a heavily doped and heavily pumped gain medium is a key issue to achieve high gain coefficient within a short interaction length since the typical L_{eff} of the SPF is of only a few millimeters. However, the traditional Er^{3+} doped silica glass has low doping concentration, sharp and narrow gain profile around 1.55 µm, a host glass with high Er^{3+} doping ability and high quantum efficiency must be required for cw-pumped evanescent amplification. Since low refractive index is another concern at the same time, fluorophosphate glass, which performs low n_D, high Er^{3+} concentration, high quantum efficiency, large absorption/emission cross section, wide and flat gain bandwidth shown in Fig. 2 is the best candidate for this work. Unfortunately, fluorophosphate glass with high Er^{3+} concentration ($> 10^{21}$ ions/cm^3), low refractive index ($n_{1550} < 1.47$) without concentration quenching is very

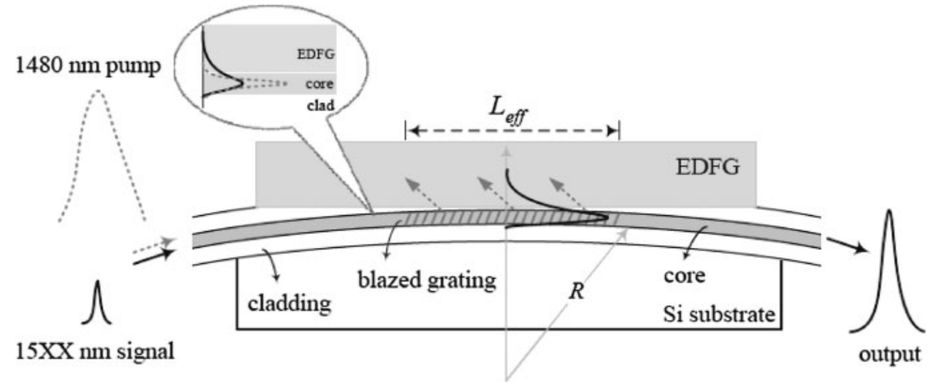

Fig. 1. Schematic of the proposed diffractive-pumping method. The inset diagram shows the conventional evanescent-pumping method where the dispersive evanescent wave tunneling makes the excitation inefficient.

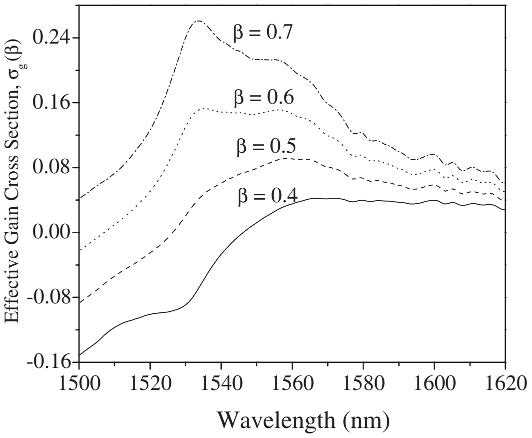

Fig. 2. Effective gain profile of Er^{3+} in fluorophosphate glass, β is the minimum population in upper level. The gain coefficient change with wavelength at different pumping energy.

Table I. Parameters of the EDFG.

Dimensions (mm)	$3.4(L) \times 9.8(W) \times 1.6(H)$
Density (g/cm^3)	4.02
Refractive index at 589.3 nm, n_D	1.4763
Refractive index at 1550 nm, n_{1550}	1.4695
Er^{3+} concentration, NEr^{3+} (ions/cm^3)	1.19×10^{21}
ErF_3 concentration (wt %)	11.1
Fluorescence lifetime, τ_f (ms)	9.0
Peak absorption cross section at 1530 nm (cm^2)	5.43×10^{-21}
Peak emission cross section at 1532 nm (cm^2)	5.99×10^{-21}
Fluorescence linewidth, FWHM (nm)	54

difficult to achieve since such high doping induces high n_D value and much larger inclination to devitrify. Our EDFG was made from Shanghai Institute of Optics and Fine Mechanics, Chinese Academy of Sciences. This is the firstly reported laser glass with such low n_D, high Er^{3+} concentration and no quenching. Nevertheless, the ion pairs increase with doping concentration and can reduce the pumping efficiency and optical gain. This EDFG is highly-enriched with fluoride with its glass composition described in mol % as $32AlF_3 11\cdot 5MgF_2 11\cdot 5CaF_2 11\cdot 5SrF_2 10\cdot 5BaF_2 3KF 9YF_3 6ErF_3 5Ba(PO_3)_2$ and the parameters of the EDFG are shown in Table I. The fluorescence lifetime (τ_f) was measured to be 9 ms using HP546800B100-MHz oscilloscope and its Er^{3+} concentration is much higher than that of the standard erbium-doped fibers, of the order of 10^{18}. To effectively guiding the fundamental mode, the index of the EDFG should be lower than the n_{eff} of the SPF so as to keep the active-side V-value in the ranging of 0.6 to 2.405.[8)]

Since the refractive index of the EDFG is still much higher than the silica, a high numerical aperture (NA) fiber is necessary to meet the requirements for total internal reflection. The single-mode fiber used is HNA15A8 (Prime Optical Fiber) with the NA, core and cladding diameters of 0.28, 3.75, and 80 µm respectively. It contains 25 mol % Ge in core and was hydrogenated to improve photosensitivity. A 10° tilted grating was inscribed with the period of 501 nm and the length of 8 mm. A longer length and a stronger index modulation of the grating are beneficial to obtain broadband diffraction for efficiently coupling the broadband 1480 nm pump laser light into radiation modes. During fabrication, a broadband 1480 nm superluminescent diode (1480-SLD) was used to measure the transmission and reflection spectra of the blazed grating as shown in Fig. 3(a), where the diffraction efficiency for 1479.76 nm (λ_{blaze}) is estimated to be 97.76%. Before side-polishing, the diffraction orientation of the grating was fixed and the fibers were then embedded and glued into the curved Si V-grooves for precision polishing.[13)] The radius of curvature R of the V-grooves is 30 m and the central remained cladding thickness was 0.5 µm after polishing. The n_{eff} and the L_{eff} of the SPF at 1.55 µm wavelength were respectively calibrated to be 1.466 and 16 mm by liquid-drop experiments.[13)] This L_{eff} is much longer than previous works[9,10)] and that is one of the key factors to obtain cw-pumped evanescent gain.

To investigate the dispersive evanescent wave tunneling between the EDFG and SPF, the white light sources comprising multiple SLDs of 980 nm and of from 1250 to 1650 nm wavelength were respectively launched into the side-polished HNA15A8 fiber (HNA-SPF) while the EDFG overlaying the polished surface with low-index Cargille liquid ($n_D = 1.440$) at the interface. Since the refractive index of the EDFG is higher than n_{eff} of the HNA-SPF at 1550 nm wavelength, the waveguiding was deteriorated at 1550 nm and the transmission output power became strongly lossy. However, large amount of power was still confined to propagate in core for 980 nm wavelength and which means

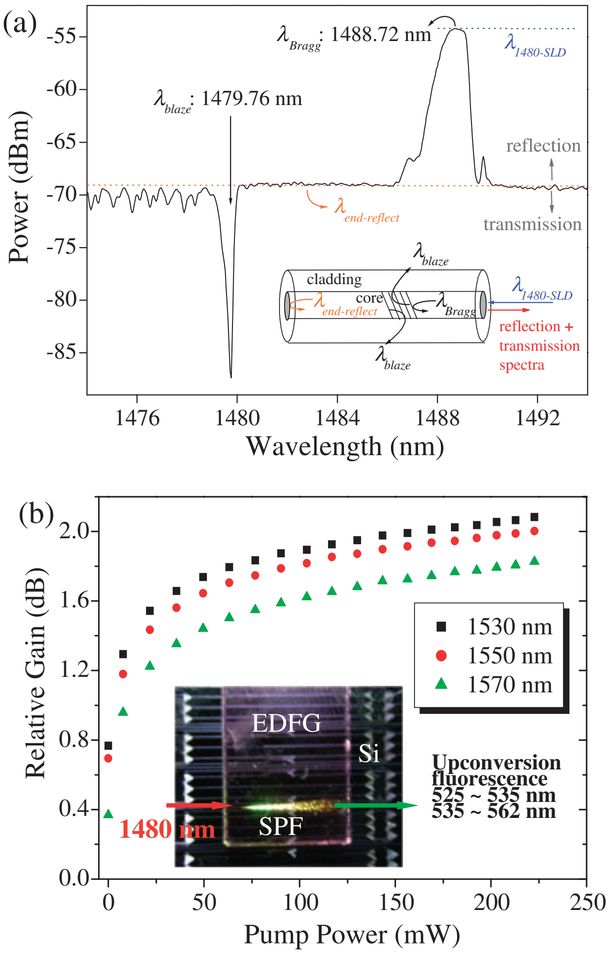

Fig. 3. (a) The measured transmission and reflection spectra of the blazed grating and (b) amplification characteristics of the wavelengths at 1530, 1550, and 1570 nm wavelengths.

that the evanescent wave tunneling between the EDFG and HNA-SPF is quite dispersive[13] and thus optical amplification based on the cw evanescent-pumping turns out to be very difficult. Subsequently, the DFB signal laser lights of 1530, 1550, and 1570 nm were respectively launched into the HNA-SPF with a blazed grating inside via a 40× objective while the 250 mW 1480 nm pump laser light was simultaneously coupled into the fiber. The coupling efficiency is only about 26% for 1480 nm and 20% for 1550 nm wavelength. At this stage our exposed narrow-band blazed Bragg gratings were still too weak to greatly manifest the advantages of the diffractive-pumping. A blazed chirped grating may be employed to efficiently diffract the broadband pump light in the future. By attaching the 13.4-mm-long EDFG on the HNA-SPF to investigate the signal gain, plenty of the pump and signal powers were refracted outside the SPF since the refractive index of the EDFG is higher than n_{eff} of the SPF. For the remained reflected signal powers, the characteristics of the relative gain are shown in Fig. 3(b) where the pump power represents the total output power of the pump laser but not the net absorption power of the EDFG. A maximum 2 dB relative gain going saturated at 1530 nm wavelength was successfully measured. Though only the relative gain was obtained, the net gain was promising since this heavily doped glass was heavily pumped by the refracted pump light and the refracted signals were also amplified through the EDFG but merely were not guided. The saturation gain can be improved by enhancing the optical uniformity of the EDFG to suppress the generations of phonons, which can be down by decreasing Er^{3+} concentration to $(8-9) \times 10^{20}$ ions/cm^3. In Fig. 3(b), the inset picture shows the refracted multistep cooperative upconversion fluorescence excited by the refracted 1480 nm pump laser and their emission spectra were 525–535 nm ($^2H_{11/2} \rightarrow {}^4I_{15/2}$ multiplet) and 535–562 nm ($^4S_{3/2} \rightarrow {}^4I_{15/2}$ multiplet).

We have demonstrated the first cw-pumped evanescent amplification at the communication wavelengths by using a heavily Er^{3+}-doped fluorophosphates glass on the side-polished fiber. This heavily doped and heavily pumped laser glass and the 16-mm-long effective interaction length of the polished fiber make the cw-pumped evanescent amplification successful. The Er^{3+} concentration is almost thousand times than that of the standard erbium-doped fiber without clustering. The upconversion fluorescence resulted from the ion pairs is interesting for the future study on upconversion fiber lasers. Based on the diffractive-pumping method, a blazed chirped grating centered at 980 nm with wider diffraction bandwidth is expected to greatly improve the gain efficiency for ultra-low-noise Er^{3+}-doped fiber amplifiers as high sensitivity photomultipliers in the future.

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