Observation of green lasing at 537 nm from Er-ions by coupled photon–atom modes in a random cavity

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Abstract
We present new results of a laser phenomenon that gives rise to a narrow green emission mode in a random photonic-crystal cavity based on an Er-doped glass–air gap–polymer with a 976 nm diode laser pump. Lasing occurs at 537 nm, which does not respond to the resonant radiative transition \( ^2\text{H}_{11/2} \rightarrow ^4\text{I}_{15/2}; ^4\text{S}_{3/2} \rightarrow ^4\text{I}_{15/2} \) in Erbium ions. This effect can be seen as photon–atom coupling in the context of the interaction between a single atom and/or a few atoms and resonant optical media, such as cavities or photonic crystals. Experimental results show that the random lasing mode directly originates from the coupled photon–atom mode inside the random cavity. The measured \( Q \)-factor is of 2100–2800 for a random cavity with an air gap of 600–1700 nm between Er-doped glass fiber and a coated polymer layer.

Keywords: random laser, coupled photon-atom modes, Er-doped glasses

Classification numbers: 5.03, 5.04, 5.05

1. Introduction
Random lasers are a new type of laser source, whose cavity is formed randomly by structured materials for photonic crystals and/or by multiple scattering in a disordered gain medium. In the last decade, although many detailed experimental and theoretical studies on random lasers have been performed [1–6], the underlying mechanism for this laser was not fully understood. The optical amplification and coherent feedback are the essential conditions for a laser. In common lasers, these processes are carried out in a resonant cavity consisting of two mirrors and the lasing wavelength responds to radiative transition between the upper lasing level and the lower ground state of the active atoms. Random lasing with non-resonant feedback is seen as a remarkable narrowing of the luminescence spectrum to a single peak of a width of about several nanometers, while coherent feedback lasing is identified as a series of high and narrow peaks, the width of which decreases with increased pump power to at least the tenth nanometer scale [7]. In addition, more interference effects were recognized, such as the spatial correlations in the intensity transmitted through random media [8]. These experiments were performed on passive random media. Two different theoretical approaches to random lasing can be distinguished. The analysis of average system response performed within the diffusion model possibly includes coherent backscattering corrections, but it fails to predict the lasing threshold behavior for the laser action. The rare fluctuation leads to the formation of high quality random cavities that are responsible for lasing and the right method should be based on a microscopic approach. On the other hand, the experimental studies of atom–photon interaction between single and/or a few atoms and a resonant optical cavity [9, 10], which has attracted much interest for both fundamental, leading to a better understanding of atom–cavity coupling and/or photon–electron interactions, and has been applied to controlling spontaneous emission for the thresholdless lasers [11–13].

In this paper we report on the observation of green lasing emissions in amplified Er-doped fiber with a cavity...
randomly created by a glass–air gap–polymer cover on the fiber that leads to narrow emission at 537 nm, which does not correspond to any emission wavelength from radiative transition in the Er ions. We describe detailed measurements of up-conversion emission from Er-doped fibers pumped by a laser diode at 976 nm in cases with and/or without random cavity. We also concentrate on Erbium atom–cavity interaction in the cavity to explain lasing emission at a wavelength of 537 nm. Besides relying on simple implementation, the obtained effect should lead to useful applications in the photonic cavity laser technique and optical sensors.

2. Experimental setup

In common cases, the up-conversion emission of the Er-doped silica fiber pumped by a laser beam at 976 nm is a broad-band fluorescence emission with two peaks at wavelengths of $\lambda_1 = 522$ nm and $\lambda_2 = 547$ nm, which correspond to radiative transitions $^2H_{11}/2 \rightarrow ^4I_{15}/2$ and $^4S_{3}/2 \rightarrow ^4I_{15}/2$ in Erbium ions. But when observing the emitted light in a direction almost perpendicular (or maybe perpendicular) to the fiber axes, we find a very thin spectrum line of increased intensity with a wavelength of 537 nm in experiment. It is interesting to note that the wavelength of 537 nm does not respond to any radiative transitions in Erbium ions. The scheme of the experimental setup for studying a random cavity in Er-doped silica fiber is demonstrated in figure 1. We used commercial single-mode Er-doped germano-silica fibers HCO-4000 from CorActive (France) with an Erbium concentration of about 4000 ppm. The pump is a laser diode with an output power adjusted from 0 to 165 mW at a wavelength of 976 nm and the pumped light directed along the fiber (i.e. the end-pumping method). The emission spectra were measured by High resolution Spectrometer (Imaging Microscopy Spectrograph) with a spectral resolution of 0.1 nm and a light power sensitivity of $-90$ dBm. The proposed random cavity has the structure of a silica glass–air gap–polymer layer that has different indices and light can reflect at the interfaces between them. The structure of the random microcavity is imaged by Ultra-high Resolution Field-Emission Scanning Electron Microscopy (FE-SEM) S-4800.

3. Results and discussion

The proposed random cavity in the optical fiber is proved by a SEM image. Figure 2 presents the structure of the random cavity created by a silica glass–air gap–polymer layer imaged by SEM S-4800. We obtained the air-gap thickness of 600–1750 nm. This structure leads to light reflection at the interfaces of layers with different refractive indices. From the reflection at interfaces of the structured materials, we find that the reflected light has a significant intensity if the optical path difference equals $k \lambda$ ($k$ is an integer), then $\lambda$ is called the resonant wavelength in the cavity.

Figure 3 shows experimentally observed green emission spectra from Erbium-doped optical fiber: (a) lasing spectra at 537 nm by the coupled photon-atom mode in the random cavity, and (b) broad-band upconversion fluorescence emission spectrum with two peaks at 522 nm and 547 nm.
537 nm lasing emission intensity versus the 976 nm-laser pump power. Inset: spectrum at 537 nm versus pumped power.

Figure 5. Spectrum of light emission and air-gap thickness of about 950 nm, the light at 537 nm with a narrow line width was emitted.

547 nm, which responded to radiative transitions $^2H_{11/2} \rightarrow ^4I_{15/2}$ and $^4S_{3/2} \rightarrow ^4I_{15/2}$ in Er ions, respectively. The measured line-width of the laser spectra was of 0.2–0.25 nm, which means that the Q-factor of the random cavity was 2100–2800. Figure 4 demonstrates the intensity of 537 nm narrow line-width emission as a function of the pump intensity at 976 nm.

Upon increasing the pumped intensity, the 537 nm green light intensity stays in the linear lasing regime. It should be noted that the lasing threshold was very low (at a pumped power of 2–3 mW for 6 m long Er-doped fiber) and the laser output remains linear with respect to the optical pump power, even at some tens times above threshold.

For testing the formation of a random cavity that has the structure of a glass--air gap–polymer cover, we destroyed the air-gap in three ways: (i) removing the coated polymer cover, (ii) destroying the air-gap by depressing the polymer cover and (iii) covering the polymer layer with water and/or alcohol. For the first two cases (without the air-gap in the structure of the fiber), the emission at 537 nm disappeared, which means that the cavity of the laser was absolutely destroyed (see figure 5). In the last case, the 537 nm emission intensity did not disappear.

Figure 6 shows the spectra of 537 nm emissions from the Er-doped fiber with a polymer layer covered by water drops. The intensity of the emitted light at 537 nm was reduced by scattering on the fiber surface.

We obtained series of green lasers emitted at 537 nm along the fiber. The lasing intensity depended upon the pumped power at the position of the random laser and the laser intensity monotone decreased along the fiber from the starting pump position (see figure 7).

Using the model of the coupled photon–atom modes in the cavity, we proposed that the 537 nm lasing emission from Er ions in the fiber can appear due to the following factors. A diode laser operating at 976 nm pumps the Er ions from
their fundamental level $^4I_{15/2}$ to $^2I_{11/2}$ and a second photon transfers the excited ion to either $^4F_{7/2}$. This level decays very rapidly to the levels $^2H_{11/2}$ and $^4S_{3/2}$. The splitting of these levels is only some hundreds of cm$^{-1}$ and the inversion can be achieved between the level $^4S_{3/2}$ and the upper Stark levels of the ground state $^4I_{15/2}$ [14]. In our case, the emission at 537 nm does not respond to any radiative transition in the Erbium atoms. The experimental evidence shows that the photon–atom interaction appeared due to a cavity randomly created in the glass fiber–air gap–polymer layer cover, which has a $Q$-factor of 2100–2800. From the theory of interactions between the cavity-resonant photon and the excited Er ions on the upper levels $^2H_{11/2}$ and $^4S_{3/2}$, the Er ion population on the state $^4S_{3/2}$ may be more than on $^2H_{11/2}$, and the different value of the resonant photon energy and radiative energy of the transition $^4S_{3/2}$$^4I_{15/2}$ is very small in the experiment (equal to 42 meV). We can determine that the probability of interaction of a photon-excited atom on state $^4S_{3/2}$ would be more than with an atom on state $^2H_{11/2}$ in the cavity.

4. Conclusion

We have observed the green lasing emission at 537 nm from an Er-doped optical fiber pumped by a 976 nm laser diode. The lasing wavelength at 537 nm did not respond to any radiative transitions in the Erbium atoms. The experimental evidence shows that the photon–atom interaction appeared due to a cavity randomly created in the glass fiber–air gap–polymer layer cover, which has a $Q$-factor of 2100–2800. From the theory of interactions between the cavity-resonant photon and the excited Er ions on the upper levels, we can explain the phenomenon of the emission of photon energy differing from the radiative transition energy of the atoms. It is remarkable that we can obtain a series of random cavity lasers along the Er-doped silica fiber. This is the first step toward a novel green laser with adjusting emission wavelengths based on Er-doped fibers for optical sensors.

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