Modeling and Simulation of Output Spectrum of Quantum Dot Doped Broadband Fiber Light Source in 1200-1700 nm Range

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Abstract. In the face of the demand for increased communication capacity of fiber optic communication and the requirement for accuracy and stability of various fiber optic devices, the light source, as one of the key devices, is also required to have higher bandwidth and output power. In this paper, this study model and simulate the output spectrum of a quantum-doped optical fiber light source in the range of 1200nm to 1700nm. The rate equation and power propagation equation are established based on the energy level structure of quantum dots. MATLAB solves the numerical model to obtain the output spectra of quantum dot-doped optical fiber light source under different variables. The fiber length, doping concentration, and pumping optical power was further varied to study the effects of several variables on the peak output spectrum. The results show that the fiber length and doping concentration increase and then decrease the peak value of the output spectrum while the pump power increases the peak value of the output spectrum. A pump power of 200 mW was chosen to obtain good experimental results at a fiber length of 3 m and a doping concentration of $4\text{x}10^{24}/\text{m}^3$. The maximum output power is 4.9 mW, and the spectral line width is about 80 nm. The maximum output power is 69 mW, and the spectral line width is about 100 nm at a fiber length of 4 m and a doping concentration of $4\text{x}10^{24}/\text{m}^3$ with a pump power of 400 mW.

Keywords: Fiber Optic Light Source; Quantum Dots; Numerical Model; Output Spectrum.

1. Introduction

With the widespread use of the information society and the common use of fiber optics, greater information capacity and higher information quality have become an inevitable demand, so the gain devices in fiber optic communications, in terms of increasing bandwidth, capacity, rate, and other aspects of higher demand. Fiber optic communication is developing rapidly in the direction of high speed, high capacity, wide bandwidth, long distance and low cost, and the key device of fiber optic communication - the light source also has higher requirements.

Broadband fiber optic light sources have important uses in spectral analysis, fiber optic communication, fiber optic sensing, etc. [1]. The development of fiber amplifiers and lasers has also led to the creation of spontaneous broadband emission (ASE) light sources based on the amplification of optical fibers doped with rare earth elements and the first pioneering use of erbium-doped ASE light sources in fiber optic gyroscopes at Stanford University in 1989[2]. Erbium-doped ASE light sources are now on the market and offer a wide spectrum, high power, and steady average wavelength. It is a crucial light source for testing optical components in DWDM systems, fiber optic gyroscopes, and multi-wavelength light source applications for spectrum segmentation in access networks. In recent years, the current research progress of broadband fiber optic light sources at home and abroad mainly focuses on erbium-doped fiber optic light sources.

In 2018, Petrov et al. investigated a super fluorescent fiber with a high-purity erbium-doped fiber and two pumping wavelengths, a light source capable of producing spectral widths above 80 nm with coherent and decoherent lengths of 7 um and 85 um[3].

The effect of light source output power, spectral width, and average wavelength was tested by Fang Hong et al. in 2015, and the pumping power and EDF length were optimized so that the stability of the light source was influenced by these two factors [4]. Li Li and Zhenan Jia developed a two-stage dual-channel dual-pumped erbium-doped SFS in 2016. They analyzed its output power, the flatness of the spectrum, and the variation of the average wavelength. Optimizing the two-stage EDF's

length and pumping power, the average wavelength was l566.4 rl/n, the output power was 16.89 mW, and the unevenness was less than ± 2 dB [5]. Li Li and Zhenan Jia performed spectral smoothing of EDSFS using the epitaxial flattening technique in 2017. They compared it with the current commonly used epitaxial flattening technique, and the results showed that the gain flattening technique using long-period gratings is more practical[6]. In the same year, Yan Li et al. conducted an in-depth discussion on the effect of EDF output performance. They found that the output power, spectral width, and average wavelength all decreased, while gamma radiation had the greatest effect on the output power [7]. As can be seen, most of the existing studies focus on erbium-doped fiber optic light sources, and there are fewer studies on quantum-doped fiber optic light sources. This paper focuses on a quantum-doped fiber optic light source and studies the output power and spectral width of ASE light from a quantum-doped fiber optic light source.

Quantum dots (QDs) have been greatly researched and applied as light-emitting materials in recent years due to their high quantum yield and tunable absorption-radiation peak wavelength[8]. In fiber optic communication, more research is done on quantum dots, such as PbSe and PbS of group IV-VI. The existing optical fiber communication field expects a wider band. PbSe, PbS, And other quantum dots have a larger Bohr radius and narrower forbidden bandwidth, making their infrared spectra have a larger range [9], so there is a broad research prospect.

PbSe Quantum dots are easily oxidized in the atmosphere, resulting in lower quantum efficiency. PbS Quantum dots, on the other hand, are less susceptible to oxidation, more spectrally stable, and the existing preparation techniques are relatively mature. Therefore, PbS quantum dots have been used in various optical fiber devices for many applications and research [10].

In quantum dot optical fibers, the optical fibers obtained by techniques such as chemical vapor deposition have a full width at half peak (FWHM) of photoluminescence (PL) of about 130 nm, covering the wavelength region of 1100~1300 nm [11]. The QDF obtained by melt drawing and heat treatment in a glass tube reduces the transmission loss of QDF, and its PL spectrum covers 1000-1700 nm with an FWHM of 297-316 nm [12]. The QDF with a single waveguide structure was fabricated by dispersing PbS quantum dots in UV-cured polymer by UV lithography. The wavelength of the QDF is 1080 nm, and the bandwidth is about 200 nm [13].

In quantum dot fiber amplifiers (QDFA), related research has been developed along three main paths. The first is a QDFA based on a fusion cone-type fiber coupled structure, using transient wave excitation quantum dots to generate PL, thus amplifying signal light. A stable gain output of 17 dB is obtained for an incident signal optical power of -63 dBm at the central peak wavelength of 1550 nm and a bandwidth of 1440~1640 nm [14]. The second type is the quantum dot fiber amplifier with liquid, or liquid solidified fiber core. In recent years, UV gel has been used as the core substrate, and PbSe or PbS colloidal quantum dots are mixed and pumped into the hollow core fiber to form a quantum dot fiber [1]. The third type is the quantum dot fiber amplifier with a glass core substrate. The glass core substrate PbSe doped quantum dot fiber amplifier is prepared by the high-temperature melting method, if the central particle size of 5.88 nm quantum dots, the operating wavelength region can be extended to the L-band [15].

This paper is based on the energy level structure of the quantum dot introduced. The quantum dot power transmission equation and rate equation, based on the theoretical model, put forward the simulation of the optical fiber light source ASE output spectrum from the spectral spectrum and output power under different conditions so as to solve the doping optical fiber light source of the lack of simulation data, for the future in the quantum dot optical fiber light source and related optical fiber device practice research to provide certain reference value.

2. Theoretical model

2.1. Energy level structure

The energy level jumps of quantum dots are shown in Fig. 1. The quantum dot is composed of a three-energy level system, and the three simple merged energy level states constitute the multiple

energy states of the quantum dot. The multiple state's energy level spacing is narrow and significantly less than the thermal energy. As a result, the quantum dot's conduction band's particle count can approach thermal equilibrium fast, with an average duration of 4 picoseconds for equilibrium to occur. The particles at energy level 1 absorb energy and move to energy level 3 when excited by pump light. The excited state of the particles (energy level 3) lasts just a very brief period of time before the particles swiftly and radiation-free transition to energy level 2. A signal light is induced into the particle at energy level 2, and the particle then jumps to energy level 1 by spontaneous and stimulated radiation, respectively. In order to produce light amplification, the method emits photons with the same wavelength as the signal light at the same time, superimposing it.

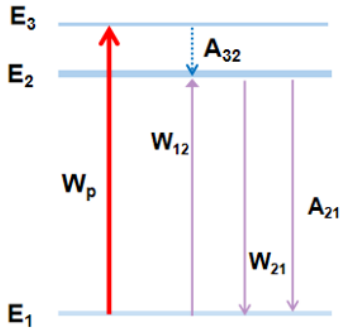


Fig 1. Energy level structure of quantum dots.

In the figure,W_p, W_{12}, W_{21}, A_{32}, A_{21} are pump light absorption rate, spontaneous radiation absorption rate, excited radiation rate, no radiation jump probability, and radiation jump probability, respectively. The particle number density of energy level 1, energy level 2, and energy level 3 are recorded as N_1 , N_2 , and N_3 , respectively. (Since the lifetime of particles at energy level 3 is very short, most particles rapidly fall to energy level 2 by radiation-free form, and very few particles fall to the ground state, so let W_{31} = 0)

2.2. Power propagation equation and rate equation

The rate at which a particle transition between energy levels changes the number of particles at each energy level is called the rate equation. The particle transition rate depends on the rate of the upper and lower energy level, and the number of particles of each energy level per unit time is related to the particle number density of the energy level itself, the energy level absorption, and the rate of radiation. The rate at which other energy level transitions increase the particle number density of the local energy level, minus the rate at which the next energy level reduces the particle number density, is the rate equation. Among them, the pump light absorption rate, spontaneous radiation absorption rate, stimulated radiation rate is proportional to the optical power, emission or absorption cross section, inversely proportional to the photon energy, fiber core cross section areaA_{eff}. Combined with the established quantum dot level structure, the rate equation of the quantum dot can be established.

In the steady state, the density of particles overtime over the three energy states is zero, meaning that the rate equation for each energy level is equal to 0. Thus, the relationship between the particle number density of each energy level and the absorption rate or the radiation rate can be obtained.

Similarly, the pump optical power and the spontaneous emission (ASE) power depend on the transfer of the optical power between the various energy levels. Because the transmission of power involves the loss of light in the material of the optical fiber, the change of power with the propagation length is related to the overlap factorΓ_{ASE} , the material loss coefficientα, the absorption cross-sectionσ_a and the emission cross-sectionσ_e of the material. Thus establishing the power propagation equation.

According to the established power propagation equation and the rate equation, the output optical power at different propagation lengths can be calculated to obtain the output spectrum, which is also the principle of establishing the simulation calculation on MATLAB.

2.3. Parameter Description

All the parameters related to the properties of quantum dots used are shown in Table 1, using PeS quantum dots as an example and using the parameters associated with the experimental environment of PeS quantum dots.

Table 1. The Parameters used in the simulation model [16].

Parameters	Value
Pump Wavelength /nm	980
Upper-level lifetime t/us	240
Pumping absorption cross-section σ13 /m2	3.4×10^{-24}
Pumping emission cross-sectionσ31 /m2	0.8×10^{-24}
Fiber core radius r/m	2.5×10^{-6}
background loss α/m-1	0.1
A32 /s-1	106

Fig. 2 shows the absorption and emission cross-section values of PeS quantum dots at different wavelengths measured in the experimental environment.

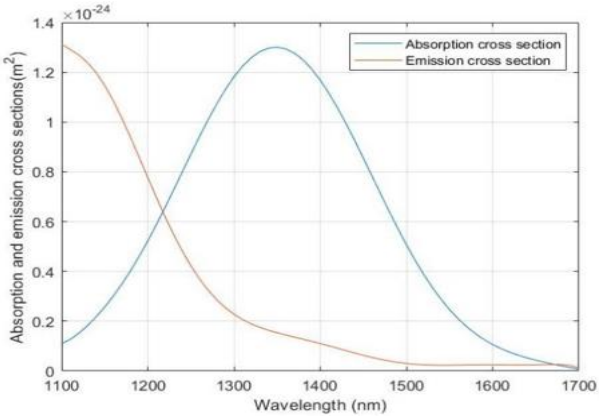


Fig 2. Variation of emission cross section and absorption cross section with wavelength [17].

3. Results and Analysis

This study simulated the above model using MATLAB and obtained the ASE output optical power spectrum under different parameter conditions. The fiber length$L = 4m$, doping concentration$N = 4x10^{24}/m^3$, and pumping optical power $Pp_0 = 200mW$ were set as the benchmark conditions. The output spectrum under the benchmark condition is shown in Fig. 3. The effects of fiber length, doping concentration and pumping optical power on the output spectra were investigated under benchmark conditions.

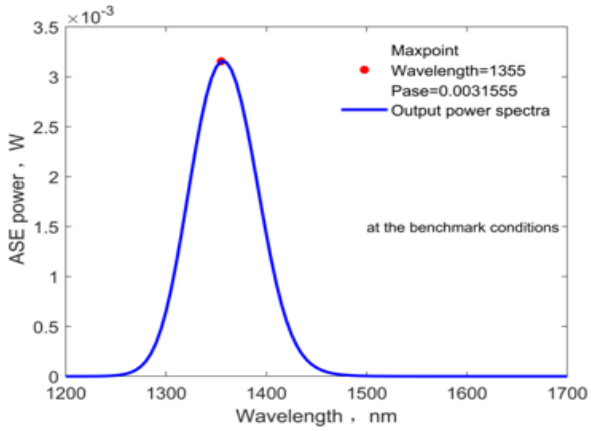


Fig 3. Output spectra under benchmark conditions.

3.1. Effect of fiber length on the output spectrum

Keeping the baseline conditions $N = 4x10^{24}/m^3$,$Pp_0 = 200mW$ constant, the output spectra of$L = 2m, L = 3m, L = 4m$ were investigated, and the results are shown in Fig. 4 (a).

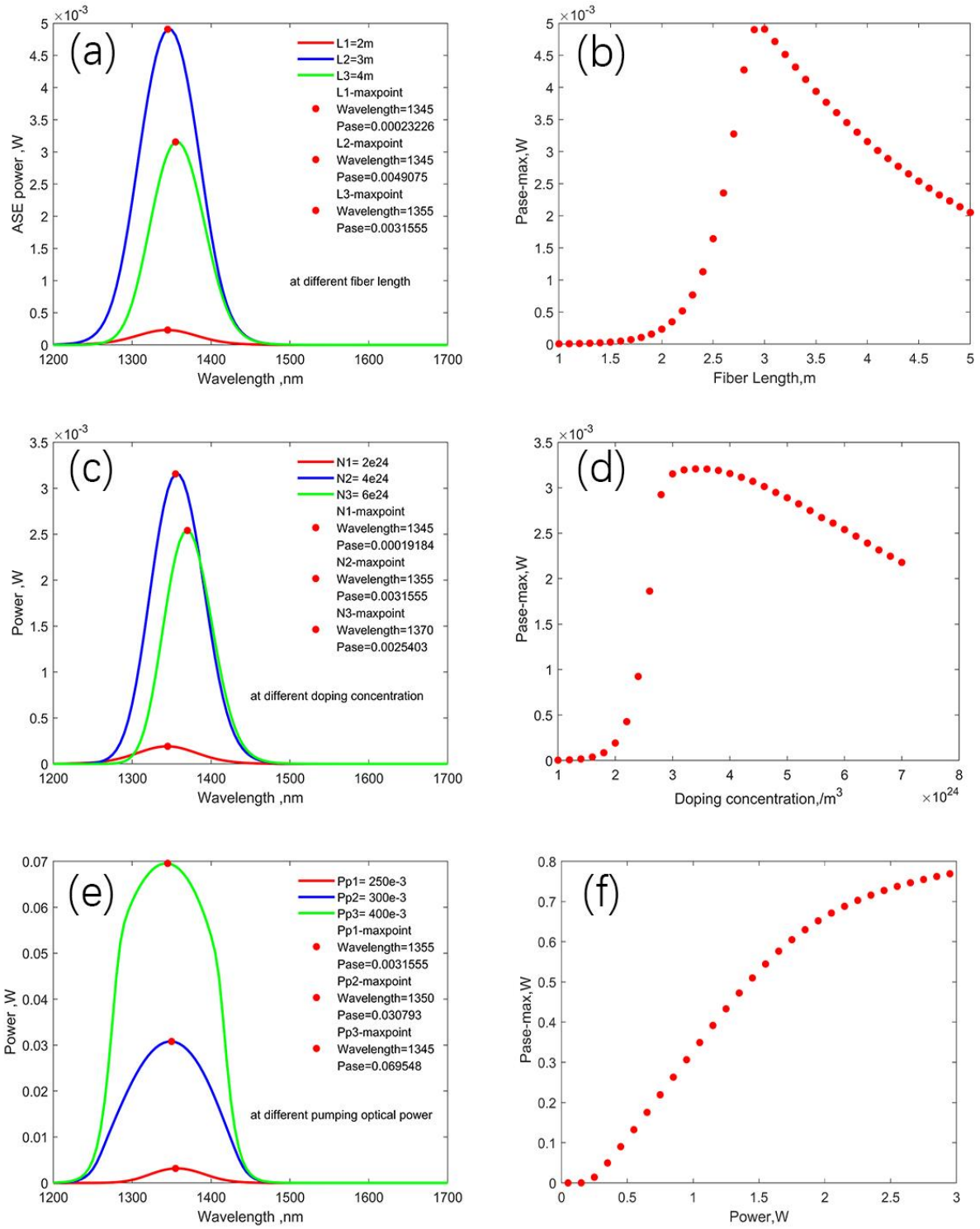


Fig 4. (a) Variation of output spectrum with fiber length
(b) Variation of peak output spectrum with fiber length
(c) Variation of output spectrum with doping concentration
(d) Variation of peak output spectrum with doping concentration
(e) Variation of output spectrum with pump optical power
(f) Variation of peak output spectrum with pump optical power.

The central wavelength is shifted compared with the reference condition$L = 4m$, but the shift is small. When L increases, the central wavelength increases slightly, which is related to the size of the emission cross-section as well as the absorption cross-section. This is related to the size of the emission cross-section as well as the absorption cross-section. The wave's peak at the central wavelength varies considerably with the fiber length change.

Therefore, this study further investigates the variation of the peak of each output spectrum with different fiber lengthsL. The results are shown in Fig. 4 (b). As the length of the fiber increases, the peak of the output spectrum increases and then decreases, which is a nonlinear variation, mainly due to the attenuation of the pump light inside the fiber as the length increases. The maximum value occurs at about $L = 3m$, grows rapidly in the range of 2-3m, and decreases equally rapidly after 3m. The change is not obvious at small fiber lengths, because at small fiber lengths, the pump light is stronger, and the attenuation of the pump light caused by the change in fiber length is not obvious. The maximum output power appears at$L = 3m$, the maximum output power is 4.9mW, and the output spectral line width is about 80nm.

3.2. Effect of doping concentration on the output spectrum

The output spectra of$N = 2x10^{24}/m^3$,$N = 4x10^{24}/m^3$ and $N = 4x10^{24}/m^3$were investigated by keeping$L = 4m$, $Pp_0 = 200mW$ constant under the reference condition, and the results are shown in Fig. 4 (b). The central wavelength has a larger shift compared to the reference condition. $N = 4x10^{24}/m^3$, and when the doping concentration increases, the shift of the central wavelength is much larger than the fiber length change. This phenomenon should be due to the different absorption and emission cross-sections at different doping concentrations, resulting in a shift of the central wavelength [1].

And the wave peak at the central wavelength has a large variation with the change of doping concentration. Therefore, the variation of the wave peak of each output spectrum with different doping concentrations N was further investigated and the results are shown in Fig. 4 (c).

With the increase of doping concentration, the peak of the output spectrum increases and then decreases, which is also nonlinear. The maximum value occurs around$N = 3.5x10^{24}/m^3$, where the maximum output power is 3.1 mW, and the spectral line width is about 70 nm. The peak of the output spectrum increases rapidly in the range of $2x10^{24}/m^3$- $3x10^{24}/m^3$, and decreases more slowly than the decrease phase caused by the fiber length when it is larger than$3x10^{24}/m^3$. The small variation in the range$1x10^{24}/m^3$-$2x10^{24}/m^3$indicates that there may be a minimum threshold in the effect of doping concentration, which needs to be greater than this value to produce output under effective conditions.

The effect of fiber length is greater than the effect of doping concentration for both the rising and falling phases of the peak output spectrum, and the overall effect of fiber length on the output spectrum is greater than the effect of doping concentration.

3.3. Effect of pumping optical power on the output spectrum

Keeping the reference condition $L = 4m$, $N = 4x10^{24}/m^3$ unchanged, the output spectra of$Pp_0 = 250mW$,$Pp_0 = 300mW$,$Pp_0 = 400mW$ were explored, and the results are shown in Fig. 4 (e).

The central wavelength offset is small. Still, the central wavelength decreases as the pumping optical power increases, which differs from the effect of the first two variables. The wave's peak at the central wavelength varies considerably with the pump's optical power change. The output spectrum's spectral line width is much larger than the first two variables, and the spectrum becomes flat rapidly with increasing pump power. Therefore, the higher power of the pump light is beneficial to obtain a flatter ASE light.

The variation of each output spectral wave peak at different pump light power Pp_0 was also further explored, and the results are shown in Fig. 4 (f). When the pump light is very small, there is a threshold value. That is, a pump light larger than the threshold value is required to produce an

effective output spectrum. As the pump power increases, the peak output spectrum increases significantly until the increase slows down when the pump light power is very large. However, in practice, the pump power used in fiber optic light sources is concentrated in the range of 100mW-500mW, and the experimental results for a large pump power are not necessarily of practical significance.

4. Conclusion

Based on the energy level structure model of quantum dots, this study established the energy level leap model of the fiber optic light source doped with quantum dots. MATLAB solved the numerical model's rate and power propagation equations, and the computational simulation of the output spectrum was performed in the 1200-1700 nm band. The effects of fiber length, doping concentration and pumping power on the ASE optical output power were analyzed. The results show that the fiber length and doping concentration have a small effect on the shift of the central wavelength, and the pump power has almost no effect on the shift of the central wavelength. For the output spectrum, the peak output power increases and then decreases with the increase of fiber length; the peak output power increases and then decreases with the growth of doping concentration; the peak output power increases and then decreases with the rise in pump optical power. In all the experimental results, the pump power of 200 mW was chosen for the low-power case. The better experimental results were obtained at the fiber length of 3 m and doping concentration of$4x10^{24}/m^3$. The maximum output power was 4.9 mW and the spectral line width was about 80 nm. The maximum output power was 69 mW and the spectral line width was about 100 nm with flat spectral lines at a fiber length of 4 m and a doping concentration of$4x10^{24}/m^3$.

However, for finding the best conditions for the output spectrum, even if the ideal combination of three variables for the output spectrum is obtained, according to the simulation results, it can be seen that the results are nonlinear. The best combination is not taken at the extreme value of the spectrum of the peak of the output spectrum with the variation of each variable simultaneously. It is still necessary to further optimize the calculation by combining the actual application conditions.

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