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Gain characteristics of quantum dot fiber amplifier based on asymmetric tapered fiber coupler

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ABSTRACT

We theoretically analyzed the gain characteristics of an integrated semiconductor quantum dot (QD) fiber amplifier (SQDFA) by using a 2 × 2 tapered fiber coupler with a PbS QD-coated layer. The asymmetric structure of the fiber coupler is designed to have a maximum working bandwidth around 1550-nm band and provide a desired optical power ratio of the output signals. By using 600 mW of 980-nm pump, 10 dB gain of a 1550-nm signal is estimated with the gain efficiency of 4.5 dB/cm.

1. Introduction

Semiconductor quantum dots (QDs) have become promising candidates as gain material in optical amplifiers, wavelength conversions, light emission diodes and etc. With a large excition Bohr radius but a small particle size, QDs present a strong effect of quantum confinement [1]. Thus, the emission and absorption of QDs show strong size-dependence, which means their spectral profile, bandwidth, and position can easily be tailored by varying the particle size and distributions for various requirements [2]. With these optical properties, optical amplifiers using QDs promise the advantages of ultra-broad bandwidth, fast gain response, high saturation power and low noise figure [3,4].

Many works have been reported on optical amplifiers taking advantage of optical emission of QDs. By using PbS QD-doped glass, Wundke et al. showed the first direct measured gain dynamics in PbS QD with a pump at 980 nm and gain observed at 1352 nm [5]. They demonstrated the tunability of the spectral position of the gain peak, which shifts from 1317 nm to 1352 nm due to the strong carrier confinement and the inhomogeneous broadening in QD-doped glass. In optical waveguide amplifier, Bakonyi et al. presented an AlGaAs-GaAs waveguide structure with a six-stack InAs-InGaAs dots-in-a-well (DWELL) gain region and obtained an optical gain of 18 dB at 1300 nm [6]. Kim et al. fabricated InAs/InGaAsP QD semiconductor optical amplifier which has a ridge waveguide structure and produce a gain of 22.5 dB in 1500-nm region [7]. Typically, QD waveguide amplifiers with 3-mm length can provide moderate gain of ∼20 dB as the QD concentration can be extended to a high level. Meanwhile, semiconductor QD-doped fiber amplifiers are also widely studied.

Cho et al. [8] developed PbTe QD-doped glass fiber using modified solution doping method in the modified chemical vapor deposition (MCVD) process. An absorption peak near 1050 nm was observed, which was attributed to the optical resonance of PbTe QD. With the same method, Watekar et al. [9] showed a PbSe QD-doped optical fiber and a broad emission in 1537-nm band was obtained upon pumping at 980 nm. Bhardwaj et al. [10] reported a PbS QD-doped glass fiber which has photoluminescence in a broadband region from 1050 to 1450 nm. However, it need carefully control the temperature in the fabrication process of QD-doped fibers as QD production is very sensitive to temperature and easily decomposes in the high temperature, which degrade the quality of QD-doped fiber. Recently, we have demonstrated a semiconductor QD fiber amplifier (SQDFA) based on a tapered single mode fiber (SMF) structure [11], in which a QD-layer is coated on the surface of tapered region. The signal is amplified over 10 dB through an enhanced evanescent wave. Besides the simple structure of such a SQDFA, advantages of low insertion loss to fiber systems and good suppression to the amplified spontaneous emission (ASE) lights are highlighted.

In this paper, we further propose an integrated SQDFA based on an asymmetric 2 × 2 tapered fiber coupler. The gain characteristics of the SQDFA are theoretically investigated, which provide a qualitative analysis of our recent experimental results [12,13]. As shown in Fig. 1a, the SQDFA is made of the fiber coupler with a QD-coated layer. The pump and signal are launched into the coupler through two input ports and the amplified signal is then detected from two output ports: one is the main path for signal

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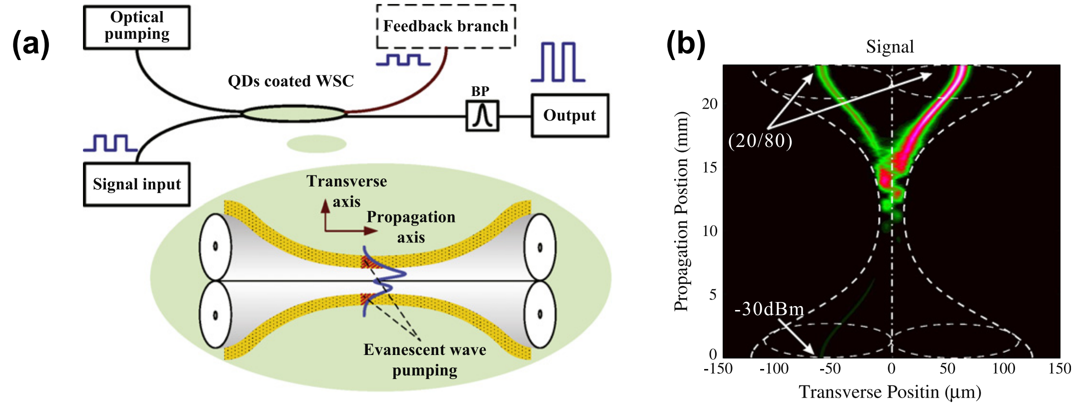

Fig. 1. (a) Diagram of SQDFA and detailed structure of QD-layer coated fiber couple. (b) Signal evolution in the fiber coupler of the SQDFA. The input power is −30 dBm at the wavelength of 1550 nm, the output power has a gain over 10 dB and a light-split ratio 20/80.

transmission and the other is used as a feedback branch, which provides a desired power ratio and thus automatic-gain-control (AGC) methods can be employed in the amplifier system [14–16]. Secondly the asymmetric structure of the fiber coupler is designed to have a maximum working bandwidth of gain. The simulation result of amplification propagation is shown in Fig. 1b. Third highlighted advantage of such SQDFAs is that it can accomplish the power amplification and the light split simultaneously, see Fig. 1b. The result of beam propagation method shows that the input signal (−30 dBm) at the wavelength of 1550 nm has a gain over 10 dB by pumping 980 nm. The power ratio of the amplified signals is 20/80.

2. Theoretical model

Due to the non-uniform structure of the tapered fiber coupler, finite difference beam propagation method (FD-BPM) [17] is employed to solve the light propagation dynamics in the fiber coupler. The shape profile of the fiber coupler is described by a dynamic shape curve [18]. Meanwhile, in each steps, a local gain/loss of the signal/pump stemming from the QD-layer is estimated according to QD energy-level system.

PbS QD is chosen among various types of QDs as it has a large excition Bohr radius of about 18 nm [19]. Thus, confinement effect and size effect are strong in the PbS QD with a diameter of several nanometers. In general, PbS QD has a strong emission in the near-infrared spectral region from 850 nm to 1800 nm [11]. The emission and absorption spectra of a 5.3 nm PbS QD is shown in Fig. 2a, in which a strong and broadband (∼150 nm) emission peak is located around 1530 nm. The first absorption peak is around 1360 nm and absorption below 1200 nm is also detected. Such emission and absorption spectra can be assigned to a two-level system, as seen in Fig. 2b. One is the ground state and the other is the upper level which includes a separated level group. In the bottom of the upper level, there are two-fine levels corresponding to the first absorption peak and the emission peak in the spectra. σ_a and σ_e correspond to the cross-section of the absorption and the emission according to Beer–Lamberts law [20]. τ_{21} indicates the recovery time of the carriers from the upper level to the ground state, namely fluorescence lifetime. The recovery time of PbS QD with a 5-nm diameter is about 1 μm [21]. In Fig. 2b, the dashed arrows correspond to the absorptions of the PbS QD while the solid arrows correspond to the emissions and the nonradiative transitions. Both the two arrows in bold describe the first absorption peak and the emission peak in the spectra.

The dynamics of the population densities in both levels is described by rate equations. In upper level, it is:

$$\frac{dN_2}{dt} = \sum_{\lambda} \frac{P_\lambda(z) i_\lambda(x,y,z)}{h\upsilon_\lambda}(N_1\sigma_{a\lambda} - N_2\sigma_{e\lambda}) - \frac{N_2}{\tau_{21}} \qquad (1)$$

where N_i denotes the population density of the ground state ($i = 1$) or the upper level ($i = 2$), $P_\lambda(z)$ is the local optical power as function of the wavelength λ and in position z, i_λ is the normalized local field intensity. In a steady-state approximation, the population density can be solved as:

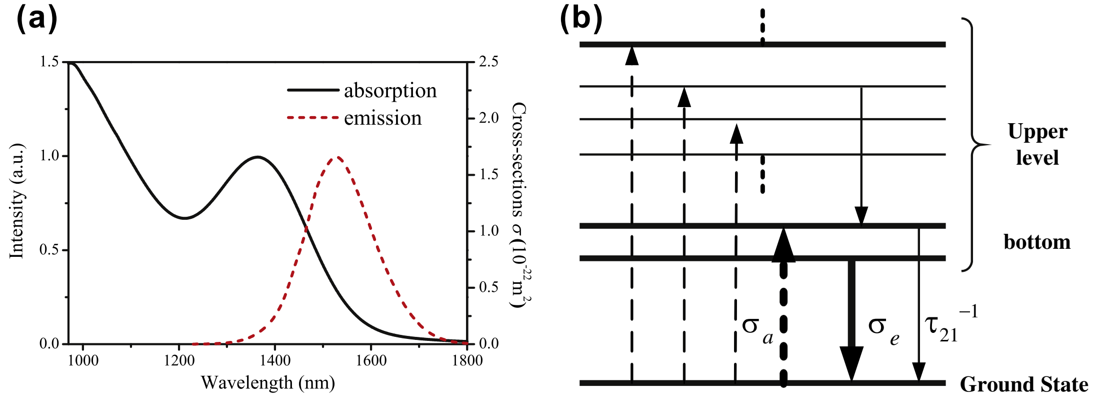

Fig. 2. (a) Absorption and emission spectra of 5.3 nm PbS QD. The first absorption peak is at 1360 nm and the emission peak is at 1530 nm. (b) Two-level system of PbS QD.