Quantum size effects in InP inner film fiber*

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Based on the semiconductor amplifiing properties and the structure of optical fiber wave guide an InP inner fiber is developed. The InP inner film fiber can be employed as a small size, broadband, and ultra-short fiber amplifier. The quantum size effects of the fiber are emphatically investigated in the work. Using the experimental data, we compare the effective mass approximation (EMA) with effective parameterization within the tight binding (EPTB) models for the accurate description of the quantum size effects in InP. The results show that the EPTB model provides an excellent description of band gap variation over a wide range of sizes. The Bohr diameter and the effective Rydberg energy of InP are calculated. Finally, the amplifiing properties of the InP inner film fiber are discussed due to the quantum size effects.

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Fiber-optical amplifier is of growing interest owing to its application to the fiber optical communication for amplifying weak optical signal[1]. Fiber optic amplifier has been widely applied to the long haul systems, metro networks and access networks[2]. The next generation of optical networks has been transferred from static networks toward more dynamic networks. The emerging ringed or mesh metro architecture has more different demands for optical amplification than that for the entrenched point-to-point architecture of the long haul systems. Thus, total node loss is the dominant contributor to total network loss in the new metro and access networks, as opposed to transmission span loss due to distance in long haul systems. More nodes in the metro and access architecture mean more optical amplifiers which will be required to overcome optical signal losses in these new dynamic networks. It is difficult to take over the task for current EDFAs that are bulky, finite band and expensive . Consequently, ultra-short amplified fibers are attractive because their extremely small size and broadband allow the construction of miniaturized amplifier systems, amplification performance of wide light spectrum and lower cost. The semiconductor film fiber[3,4] is one of the ultra-short amplified fibers. But the thickness of semiconductor film will affect the characteristics of the fiber. Especially, the semiconductor film fiber will have some extraordinary properties when the thickness of semiconductor film reaches a nanometer level.

Based on the active semiconductor film material of InP, the quantum size effects of the inner film fiber are demonstrated at the first time. The characteristics of the quantum size effects in the inner film fiber will be analyzed. The motivation for this work has found the new effects of optical fiber, which has the potential to develop broadband, high gain, ultra-short and low cost optical fiber.

The semiconductor materials of direct band gap have the advantage of its high luminescence efficiency and broadband amplified properties[5]. If these advantageous properties of semiconductor materials are combined with the optical transmission waveguide construction of optical fibers, the special optical fiber with the special functions and properties will be formed. The InP inner film fiber is an amplified one with broadband and ultra-short properties[4]. Fig. 1 shows the profile and refractive index distribution of the fiber. The InP inner film is placed between the core and the cladding of the fiber. The refractive indexes of the core, the semiconductor inner film, and the cladding are n_1, n_2, and n_3, respectively, and $n_2 > n_1 > n_3$. The optical pump mode can be used in the fiber amplifier based on InP inner film fiber. The InP is a direct band-gap semiconductor material. When the semiconductor material is pumped by a light source and the energy of the pump photon is more than that of the band gap, the excited state absorption will occur. The carriers at the valence band level will be excited to a high energy level of the conductor band. The stimulated emission takes place when the signal light passes the semiconductor layer, the carriers will be transported to the lower energy level from the high energy level in the conductor band in a short time. The material and thickness of the semiconductor film play an important role in the amplified performances of the fiber. When the InP is used as the active amplified material, the investigation of the thickness of the InP film will be very important. The bigger the thickness of the InP film is, the higher the

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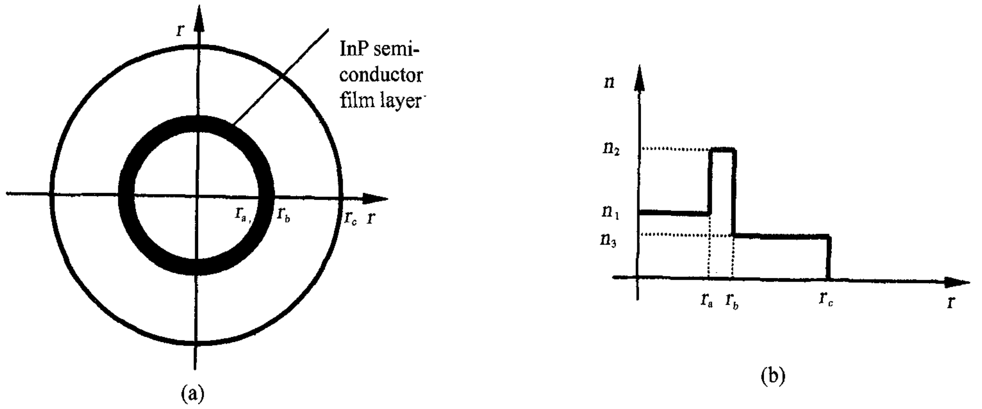

(a) The profile of the fiber (b) The fractive index distribution of the fiber

Fig. 1 The profile and refractive index distribution of the InP inner film fiber

absorption loss is, and this may lead to a failure of amplification. The semiconductor film with a thinner width (nano level) will produce a quantum size effects in the fiber. Further details will be given below with the rigorous analysis of quantum size effects of the fiber so that we can gain some insight into the basic amplified mechanism of InP inner film fiber.

At the nanometer level, the electronic and optical properties of the semiconductor material are drastically different from the bulk materials. If an electron is excited from the valence band to the conduction band of a semiconductor, the electron and hole can form a bound state which is called Wannior exciter through Coulomb interaction. The Bohr diameter of the exciter, d_B, is expressed by the following equation[6]

$$d_B = \frac{2\varepsilon_0\varepsilon_r h^2}{\pi m_0 e^2}\left[\frac{1}{m_e^*} + \frac{1}{m_h^*}\right] \tag{1}$$

where ε_r is the relative dielectric constant of the semiconductor, m_e^* and m_h^* are the effective masses of the electron and hole, respectively, m_0 is the mass of the electron. When the diameter of a nanoparticle approaches the size of the exciter Bohr diameter, the motions of the electrons and holes become confined in the nanoparticle. In this regime of spatial confinement of the charge carriers which is called particles in a box, the kinetic energy becomes quantized and the energy separation between various levels increases due to the confinement. As a result, the band gap of the semiconductor increases with decreasing particle size. The phenomenon of quantum size effects occurs.

According to the effective mass approximation model[7,8], the nanoparticle can be expressed as quantum dot. The confined potential of continuous, isotropic and homogeneous media can be simplified as an infinite deep spherical potential well. Solve Schrödinger Equation, the size dependence of the band gap (E) of a semiconductor nanoparticle can then be derived as

$$E = E_g + \frac{h^2}{2\mu m_0 d^2} - \frac{3.572e^2}{4\pi\varepsilon_0\varepsilon_r d} + 0.248E_{RY} \tag{2}$$

where E_g is the band gap of the bulk semiconductor, d is the effective diameter of the semiconductor particle, $\mu = (m_e^{*-1} + m_h^{*-1})^{-1}$, and E_{RY} is the effective Rydberg energy, $E_{RY} = h^2/(2\pi^2\mu m_0 d_B^2)$. The second term on the right of the equation is predominant for nanoparticle energy variations which represent the particle-in-a-box quantum localization energy, the Coulomb interaction between the electron and hole inside the nanoparticle is taken into account in the third term, and the fourth term represents the spatial correlation. Though EMA contains the basic physics of the quantum size effect in Eq. (2), this method is not able correctly to predict the band gap variation for very small nanoparicles, it grossly overestimates the band gap of the small sized semiconductor nanoparticles. An effective parametrization within the tight binding model[9] shows an excellent description of band gap variation over a wide range of sizes. The band gap of InP semiconductor nanoparticle can be expressed as

$$E = E_g + 100/(5.8d^2 + 27.2d + 10.4) \tag{3}$$

The parameters of InP are listed in Table 1.

Tab. 1 The parameters of InP

Parameters	InP
Band gap, E_g (eV)	1.351
Dielectric constant, ε_r	12.4
Melting Point, T_{in} (℃)	1070
Electron effective mass, m_e^*	0.077
Hole effective mass, m_h^*	0.64

Thus, the Bohr diameter of InP can be calculated from Eq. (1), $d_B = 19.4$ nm. From $E_{RY} = h^2/(2\pi^2\mu m_0 d_B^2)$ the effective Rydberg energy of InP, $E_{RY}=5.891$ meV, can be yielded. $E_{RY}=5.891$ meV, When the diameter of InP approaches the Bohr diameter, the quantum size effects become obvious. The band gap dependence on the diameter of InP nanoparticles is shown in Fig. 2 for EMA and EPTB. These curves are plotted over a wide diameter range. On the horizontal line, the diameter of nanoparticle is bigger than the Bohr diameter. The results clearly show the EPTB provides a good description of the band gap variation with the diameter of nanoparticles over the entire Bohr diameter range of size for InP, as shown by the lower solid line in the Fig. 2; the band gap variation on the basis of EMA, shown in Fig. 2 with the upper solid line, is in gross disagreement with the experimental results. EMA is suitable for larger nanoparticles.

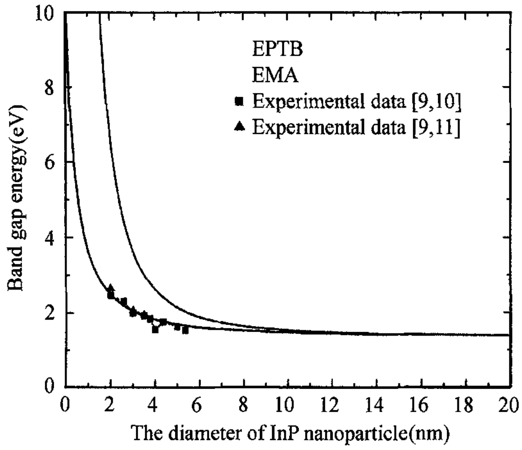

Fig. 2 The dependence of the band gap on the diameter of InP nanoparticle

It can be also seen that the band gap variation will trend a constant (E_g), when the diameter is bigger than the Bohr diameter. For EPTB the detail values is follow as:

$$d = 3\ \text{nm}, \Delta E = E - E_g = 0.693\ (\text{eV})$$
$$d = 6\ \text{nm}, \Delta E = E - E_g = 0.262\ (\text{eV})$$
$$d = 10\ \text{nm}, \Delta E = E - E_g = 0.116\ (\text{eV})$$
$$d = 19.4\ \text{nm}, \Delta E = E - E_g = 0.0355\ (\text{eV})$$

Above data show that the quantum size effects yield obviously when the diameter of the nanoparticle is less than 6 nm; but the quantum size effects disappear nearly when the diameter of the nanoparticle is bigger than the Bohr diameter. If the semiconductor film thickness of the InP inner film fiber is equivalent to the diameter of the nanoparticles (d), the quantum size effects occur also in the fiber with the approach of the film thickness to the Bohr diameter. Further discussion will be presented below.

Above analysis shows that quantum size effects could be observed in the fiber if the thickness of the semiconductor film is less than the Bohr diameter. Due to the quantum size effects the amplified properties of the InP inner film fiber will be changed. The key property changes are as follows:

(1) Both the absorption spectrum and the emission spectrum of the fiber are shifted to higher energies with decreasing the film thickness. According to the relationship between the wavelength and the band gap energy, $E\lambda=1240$, the band edge wavelength of the film thickness is shown in Fig. 3 which illustrates the amplified signal wavelengths decrease due to the quantum size effects. The maximum band edge wavelength is about 918 nm without the quantum size effects, but the band edge can reach the vacuum UV wavelength if the thickness of the InP film is about 1 nm, which shows strong quantum size effects.

(2) For bulk semiconductor material direct band gap is width between conductor and valence bands, and the free carriers can move in the different energy band, so the transition of the carriers happens between the conductor and valence bands, which leads to the great amplification noise. Due to quantum size effects the kinetic energy becomes quantized and the energy bands will split into discrete levels, and confine the moving regime of the carriers, which reduces the amplification noise.

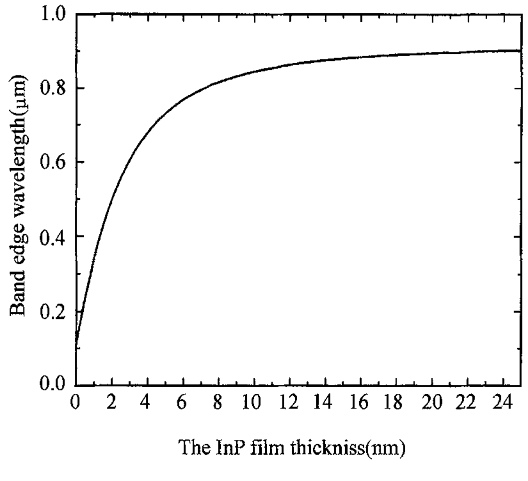

Fig. 3 Band edge wavelength of the fiber vs InP film thickness

(3) Due to quantum size effects the separation capability of semiconductor charges will be improved, the electrons and holes are confined, and the split electronic state will be quantified, the concentrations of per area of the InP carriers will be more than that without the quantum size effects. Therefore, the fiber will increase the amounts of the simulated emissions photons during the amplification of signals, which enhances the amplification efficiency.

(4) The quantum size effects increase the band gap en-

ergy. To increase band gap energy will demand for a great pumped power when the amplifier operates. This requires a balance between great band gap energy and pumped power in designing amplifier.

The quantum size effects of InP nanoparticles have been successfully investigated . The Bohr diameter of 19.4 nm of InP nanoparticles is calculated, and the effective Rydberg energy of 5.891 meV of InP is also derived. According to experimental data, EMA is compared with EPTB for the quantum size effects. The results show an excellent description of band gap variation over a wide range of sizes. Due to the quantum size effects, both the absorption spectrum and the emission spectrum of the fiber are shifted to higher energies with decreasing the film thickness; the amplification noise of the fiber amplifier will be reduced; the amplification efficiency can be enhanced; and a great pumped power should be required. All those results make the quantum size effects a promising new field for applications of broadband, ultra-short amplified fiber, and small size fiber amplifiers.

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