Linearly polarised three-colour lasing emission from an evanescent wave pumped and gain coupled fibre laser*

Pu Xiao-Yun(普小云)†, Jiang Nan(江 楠), Han De-Yu(韩德昱), Feng Yong-Li(冯永利), and Ren Yi-Tao(任一涛)

Department of Physics, Yunnan University, Kunming 650091, *China*

(Received 24 August 2009; revised manuscript received 12 October 2009)

A novel Whispering–Gallery–Mode (WGM) fibre laser, emitting linearly polarised three-colour light, is demonstrated by pumping and gain coupling with evanescent waves. The pump light is longitudinally coupled into a bare optical fibre immersed in a dye solution of lower refractive index. The dye molecules around the bare fibre are excited by the evanescent waves of pump light when they propagate along the fibre in a total internal reflection. When the pump beam within the fibre is a meridian beam, the WGM lasing emission from the fibre laser is a linearly polarised transverse electric wave, while it is a mixed wave of the linearly polarised transverse electric and magnetic waves if the pump beam is a skew beam within the fibre. Because the excited molecules are located within the evanescent field of WGM, a good spatial overlap between the dye gain and the evanescent field leads to a high pumping efficiency and a longer gain distance along the fibre. Once the bare fibre is inserted into three glass capillaries filled with Rhodamine 6G, 610 and 640 dye solutions, respectively, WGM laser oscillations at the wavelengths of 567–575, 605–614 and 656–666 nm occur simultaneously, and a linearly polarised three-colour lasing emission is achieved in a single optical fibre.

Keywords: fibre laser, Whispering–Gallery–Mode, evanescent wave, polarisation
PACC: 4255N, 4255M, 4260D

1. Introduction

Evanescent-wave gain coupled circular microcavity lasers, such as cylindrical,[1−4] spherical,[5−8] capillary[9] and fibre knot[10] lasers, have aroused much interest in recent years, which is due mainly to the fact that the gain media are distributed around their resonators and their potential applications in integrated optics, optoelectronics, optofluidics[11] etc. Because the evanescent field of Whispering–Gallery–Mode (WGM) of a circular cavity extends into the gain medium, the lasing gain can be coupled into the WGM which provides optical feedback required by lasing oscillations. To optically excite the gain molecules around a circular cavity, a laser beam is usually pumped from the outside of gain medium,[1−5] this pumping configuration is called side-pumping scheme. The side-pumping suffers a low pump efficiency, because the pump energy is absorbed by the whole excited molecules, only a small number of molecules residing in the evanescent field of WGMs contributes to the lasing gain, the others produce fluorescence which increases the lasing threshold. An idea to solve this problem is to use the evanescent-wave pumping scheme proposed in a planar waveguide early in 1972.[12] Evanescent-wave pumping scheme has been used in circular cavities in recent years, such as fibre amplification,[4] capillary lasers[8] and microfibre knot,[10] and it lows lasing threshold from a value of 200 μJ/pulse in the side-pumping scheme[1] down to 9.2 μJ/pulse[8] and further to 100 nJ/pulse.[10] In a WGM laser pumped by an evanescent wave, the pumping light is longitudinally coupled into a circular cavity when the light propagates along the axial direction of the cavity in a total internal reflection (TIR), its evanescent field excites lasing gain around the cavity, and the gain is then coupled into WGMs in the cavity. Due to a good spatial overlap between the gain and the evanescent field of the WGMs, a higher pumping efficiency has been achieved.

In the present paper, an evanescent-wave pumped and gain coupled WGM fibre laser is introduced by inserting a bare quartz fibre (no cladding layer) into a glass capillary filled with dye molecules in a lower refractive index solution. Optically pumped along the fibre's axis, the WGM lasing emission from the fibre laser is found to be a linearly polarised transverse electric wave (TE wave) when the pump beam within the fibre is a meridian beam, while it is the mixed wave of linearly polarised TE and transverse mag-

*Project supported by the National Natural Science Foundation of China (Grant Nos. 60877037 and 10564005).
†Corresponding author. E-mail: xypu@163.com
© 2010 Chinese Physical Society and IOP Publishing Ltd

netic wave (TM waves) when the pump beam is a skew beam. Once the bare fibre is inserted into three glass capillaries filled with Rhodamine 6G, Rhodamine 610 and Rhodamine 640 dye solutions, respectively, WGM laser oscillations at the wavelengths of 567–575, 605–614 and 656–666 nm occur simultaneously, and a linearly polarised three-colour lasing emission is achieved in a single optical fibre.

2. Experimental setup

The experimental setup is shown in Fig. 1 schematically. A laser beam (532.0 nm), generated by a frequency doubled and Q-switched Nd:YAG laser, was used as a pump light. The required pump energy was obtained by changing the polarisation direction of a polariser (P_1), and its power was monitored by a power meter (PM) through a beam splitter (BS). Another polariser (P_2) was used to determine the polarisation state of the pumping light. An bare fibre (F_1, 196 μm$\pm$1 μm in diameter, refractive index 1.458) was inserted into a long glass capillary (C, 1 mm in inner diameter), the residual space between F_1 and C was filled with ethanol and ethylene-glycol mixed solution doped by Rhodamine 6G dye with a concentration of 3×10^{-3} mol. The refractive index of the mixed solution, acting as the cladding solution of F_1, was 1.395 measured by an Abbe refractometer. The pump beam was longitudinally coupled into F_1 along the fibre's axis by a lens (L) (focal length = 75 mm) with a conical angle of $\theta_i = 9.2°$. The beam would propagate within F_1 by TIR if the conical angle θ_i was smaller than the critical entrance angle θ_{ic}, which was 35.6° in our experiments.

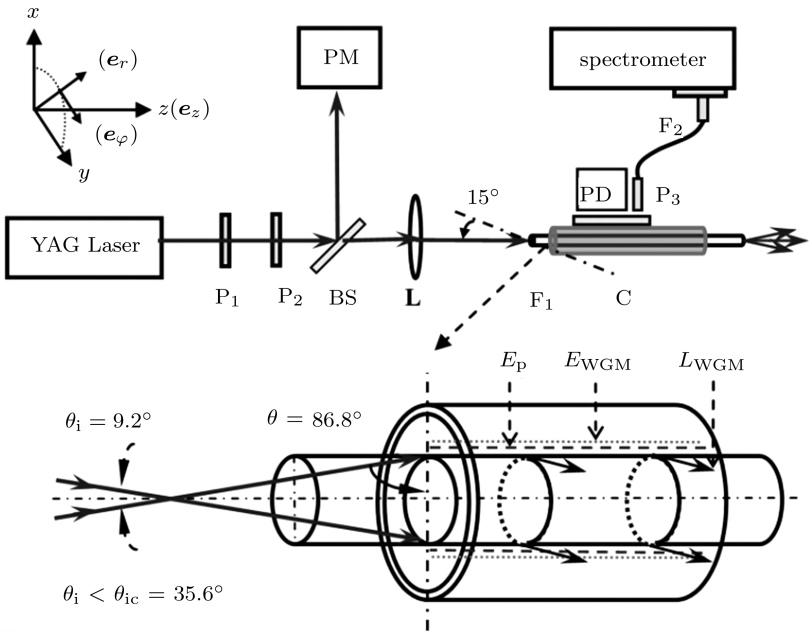


Fig. 1. Schematic diagram of experimental setup. P_1, P_2 and P_3: polariser; BS: beam splitter; PM: power meter; L: lens; F_1: bare quartz fibre; F_2: optical fibre; C: glass capillary; PD: photo-detector; E_P: evanescent field of pump light; E_{WGM}: evanescent field of WGM; L_{WGM}: WGM laser radiation.

The evanescent field of the pump light (E_p) excites dye molecules in the mixed solution, thus the photons in the evanescent field of WGM (E_{WGM}) of a circular cavity stimulate the excited dye molecules, and the E_{WGM} also couples dye gain into the circular cavity at the same time. Supported by the WGMs, lasing oscillations occur in the circular cavity. The WGM lasing emission (L_{WGM}) from the rim of F_1 can be recorded by a spectrometer (Spectrapro 500 i) equipped with an ICCD detector (PI-Max 1024RB) via an optical fibre F_2, it gives 0.05 nm spectral resolution when a grating of density 2400 g/mm is used. The intensity of L_{WGM} is detected by a photo detector (PD, DSi200) after the lasing emission passing through an analyser P_3 positioned on the yz plane. The angle between P_3 and the y-axis is defined as Φ

which is zero as P_3 is set to be along the y-axis, Φ can be adjusted by rotating P_3.

3. Experimental results and discussion

3.1. Pump beam strictly along optical fibre axis

To make sure the pumping beams within F_1 were all meridian beams,[13] the incident direction was set to be strictly along the axial direction of F_1 as shown in Fig. 1. When pumping energy was lower than 15 μJ/pulse, only a weak spontaneous fluorescence was observed around F_1. Once the pumping energy was higher than 15 μJ/pulse, a stronger deep-yellow light emitting from the rim of F_1 was observed in the direction vertical to the F_1's axis (xy-plane), the energy (15 μJ) was the lasing threshold corresponding to the onset of the deep-yellow light. To check the polarisation properties of the lasing emission, the pumping energy was fixed at 100 μJ/pulse, the polarisation direction of P_2 was set to be along the y-axis at first, and then the lasing intensity varying with angle Φ was recorded by the PD. From the normalised signals shown in Fig. 2(a), it can be seen that the acquired lasing intensity (solid points with error bars) reaches its maximum as the polarisation direction of P_3 is vertical to the F_1's axis ($\Phi = 0°$, 180° and 360°). It becomes dark as P_3 is parallel to the F_1's axis ($\Phi = 90°$ and 270°). The curve in Fig. 2(a) is calculated by Malu's law ($I = \cos^2 \Phi$), and a good agreement between the law and the experimental data indicates that when the pump beam is strictly along the F_1's axis, the electrical vectors of the lasing emission are perpendicular to the fibre's axis, and the evanescent-wave pumped WGM lasing emission is of a typical TE wave. To verify the dependence of the lasing emission on the polarisation of the pump light, the polariser P_2 was firstly set to be along the x-axis, and then 45° with respect to the x-axis in the xy plane, respectively. It was found that the experimental results were the same as that value once P_2 was set to be along the y-axis direction, which indicates that the polarisation of evanescent-wave pumped WGM fibre laser is independent of the polarisation states of the pump light.

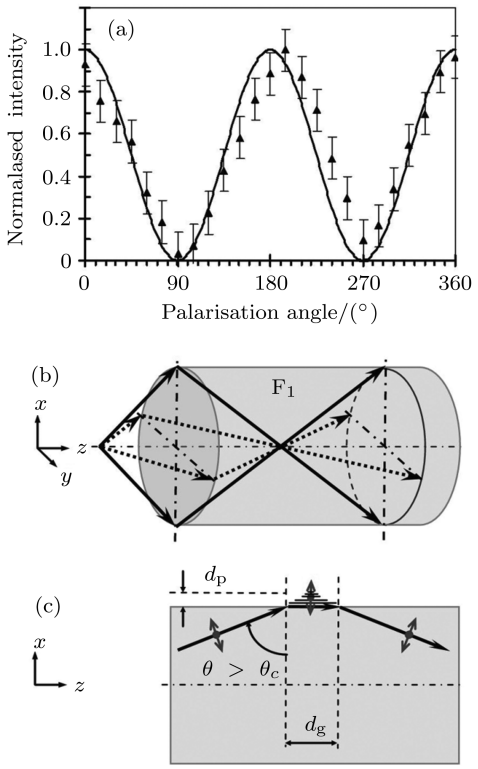


Fig. 2. Intensity of the fibre laser varying with polarisation angel of polariser P_3 (a), meridian beams propagating within a fibre (b), and polarisation status of a pump beam inside and outside a fibre (c).

When a pump beam is longitudinally coupled into F_1 along its axis as shown in Fig. 2(b), the beam in F_1 is a meridian beam, which propagates within the fibre by TIR and crosses at the fibre's axis for each reflection. For simplicity, a pump beam in xz-plane is taken as an analytic beam shown in Fig. 2(c). When the meridian beam is incident on the interface of F_1, the beam experiences a Goos–Hänchen shift[14] (d_g) and then is totally reflected by the interface of the fibre if the entrance angle θ is larger than the critical angle θ_c, where d_g is on the order of the input wavelength (λ_p). Along the distance of d_g, the light tunnels the fibre out a distance of d_p that is also a length of λ_p, thus an evanescent field of the pump light (E_p) is formed outside F_1. E_p is a traveling wave along the z-axis, which is not relevant to the polarisation statue of the pump beam within the fibre. That means that E_p cannot travel along the x-axis, and there is no z-component for the evanescent field of the pump light. For an evanescent wave pumped fibre laser, it is impossible to generate the stimulated photons polarising in the direction of z-axis. After dye gain is coupled into F_1, the WGM lasing oscillation, of course, lacks

a polarisation component of the z-axis, and the lasing emission is certainly a linearly polarised TE wave.

3.2. Pump beam deviating from optical fibre axis

To couple the pump beam into F_1 in the form of a skew beam,[13] F_1 was tilted to an angle about 15° with respect to z-axis as shown in Fig. 1. The lasing spectrum acquired without the polariser P_3 is shown in Fig. 3(a). The spectrum contains two groups of adjoining spectral lines, i.e. a shorter wavelength group and a longer wavelength group. The lasing spectrum with placing P_3 in the direction of y-axis is shown in Fig. 3(b), in which the group with a longer wavelength disappears, and the shorter wavelength group remains there. Once setting P_3 in the direction of z-axis, the obtained spectrum shows that the shorter wavelength group vanishes, and the longer wavelength group exists as indicated in Fig. 3(c). As a result, Fig. 3 indicates strongly that the group with the shorter wavelength belongs to TE wave, while the longer wavelength group belongs to TM wave; the lasing emission will contain both TE and TM waves when the pump beam deviates from the fibre axis.

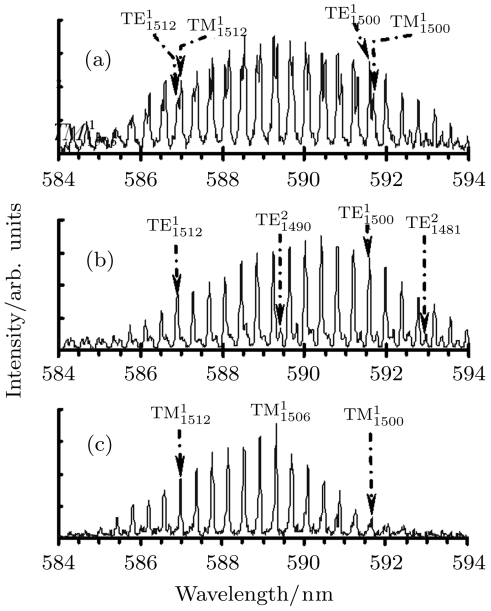


Fig. 3. WGM lasing spectra of TE and TM mixed wave acquired by pump beam deviating from the optical fibre axis in the cases without polariser P_3(a), with polariser P_3 being vertical to F_1's axis (b), and with polariser P_3 being parallel to F_1's axis (c).

3.3. Formation of TE and TM mixed waves

When a pump beam deviating from the optical fibre's axis as shown in Fig. 4(a), the beam will propagate as a skew beam in the fibre F_1 along the z-axis. To analyse its polarisation properties in detail, the beam with wave vector $\boldsymbol{k}$ in the fibre is chosen, where $\boldsymbol{k}_{xy}$ and $\boldsymbol{k}_z$ are two components of the vector $\boldsymbol{k}$ shown in Fig. 4(a) by dash arrow. $\boldsymbol{k}_{xy}$ represents a beam propagating in the xy plane by TIR, while $\boldsymbol{k}_z$ is a beam propagating along the z-axis. For the $\boldsymbol{k}_{xy}$ beam, both electric vectors (parallel and vertical to z-axis) exist simultaneously within the fibre F_1, when the light experiences TIR at the fibre's interface as shown in Fig. 4(b), it tunnels the fibre with the both electric vectors, forming an evanescent field of the pump light (E_p) outside F_1. Because the dye molecules in the evanescent field of the pump light are excited by these two different electric vectors, two kinds of stimulated photons, polarising in the z-axis and in the xy plane, exist simultaneously in the evanescent field of WGM in the fibre F_1. After the dye gain is coupled into the circular cavity, the WGM lasing oscillation and emission will contain both TE wave polarising in the xy plane and TM wave polarizing along the z-axis. It is worth noting that the wave vector in Fig. 2(b) can be also decomposed into wave vectors $\boldsymbol{k}_{xy}$ and $\boldsymbol{k}_z$. However, the vector $\boldsymbol{k}_{xy}$ does not make sense because it crosses at z-axis, which cannot travel by TIR in the xy plane of the fibre F_1.

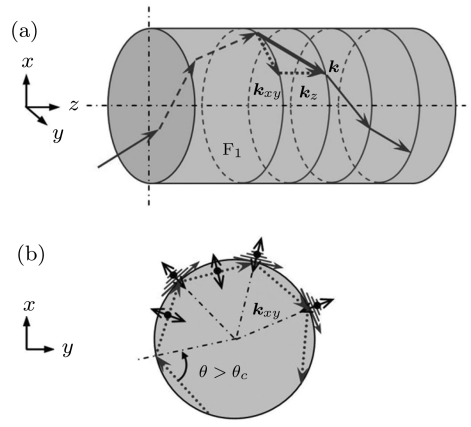


Fig. 4. Diagram to illustrate a skew beam propagating within a fibre (a) and polarised status of component $\boldsymbol{k}_{xy}$ in the xy-plane of a fibre (b).

3.4. Three-colour WGM lasing emission

It is found that the generating length of lasing emission along the F_1 increases with pumping energy

by arranging pump configuration as described in the Subsection 3.1, in which the fibre F_1 was replaced by a thick fibre (288 μm in diameter) and the direction of the incident beam was still strictly along the axial direction of F_1. When the pumping energy equaled 20, 50 and 100 μJ/pulse, the lengths of the lasing emission were 40, 90 mm and over 120 mm, respectively. Based on this, a longer gain length in evanescent-wave pumped WGM fibre laser, of course, can be utilised to build a multicolour WGM fibre laser.[15] That is to say, the fibre F_1 was inserted into three short glass capillaries (15 mm long) in series and their intervals between the capillaries were 5 mm. Rhodamine 6G, Rhodamine 610 and Rhodamine 640 dye molecules were dissolved in ethanol and ethylene-glycol mixed solution to obtain concentrations 5×10^{-4}, 2×10^{-3} and 1×10^{-2} mol, respectively. The prepared dye solutions with an index of 1.422 were filled in the residual space between the F_1 and the capillaries. Evanescently pumped by 532 nm line of the pulsed YAG laser along the fibre's axis, only a weak fluorescent light emitted out from the fibre when the pumping energy was 20 μJ/pulse. The fluorescent spectrum was recorded by a spectrometer with a grating of density 150 g/mm, which is the grey curve shown in Fig. 5(a). When pumping energy was 80 μJ/pulse, we observed three-colour (yellow, orange and red) WGM lasing emissions simultaneously in experiments, the emitting wavelengths from the fibre laser were in the ranges of 567–575 nm (Rhodamine 6G), 605–614 nm (Rhodamine 610) and 656–666 nm (Rhodamine 640) as shown in Fig. 5(a) with the black curve. Since three-colour WGM lasing emission from a single optical fibre was realised, a novel evanescent-wave pumped and gain coupled WGM fibre multicolour laser was demonstrated eventually.

To show the fine spectral structure of the three-colour WGM lasing emission, the spectra were recorded with a grating of density 2400 g/mm and shown in Figs. 5(b), 5(c) and 5(d) in the wavelengths 567–575 nm, 605–614 nm and 656–666 nm, respectively. The measured spectral intervals between two adjacent peaks are 0.246 nm (Fig. 5(b)), 0.282 nm (Fig. 5(c)) and 0.335 nm (Fig. 5(d)), which can be compared with the calculated free spectral widths of WGMs in the used circular cavity. For a larger diameter fibre (288 μm in our case), the wavelength intervals (free spectral width) can be approximately calculated by[16] $\Delta\lambda = \lambda^2/2\pi a n_1$, where a and n_1 are the radius and the refractive index of the used fibre, respectively. The calculated wavelength intervals are 0.247, 0.281 and 0.332 nm in the wavelength ranges of 567–575 nm, 605–614 nm and 656–666 nm, which accord well with the measured values.

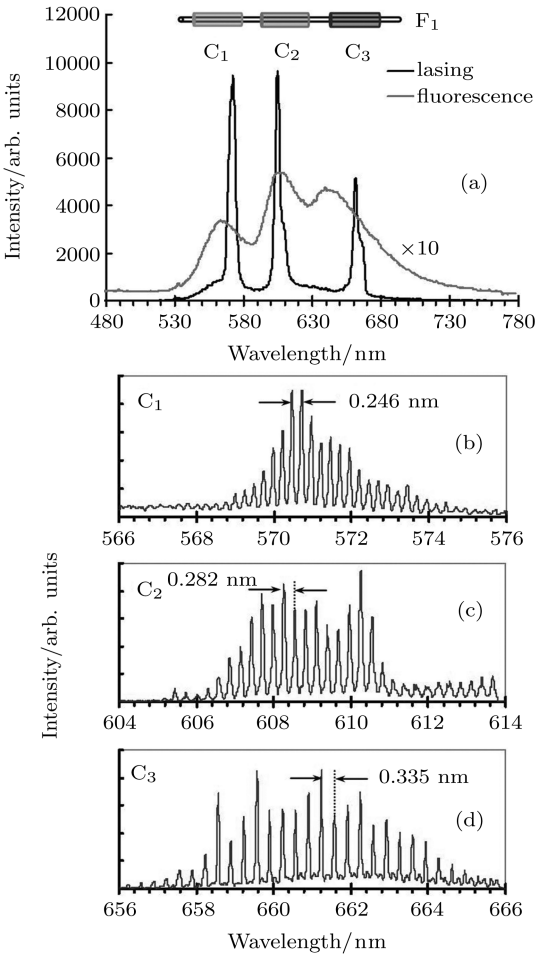


Fig. 5. Lasing spectra recorded by gratings with two different densities: 150 g/mm (a) and 2400 g/mm (b), (c) and (d). Panel (a) shows fluorescent (grey curve) and lasing (black curve) spectra emitting from a three-colour evanescent-wave fibre laser, and the laser structure in the insert, with the capillaries C_1, C_2 and C_3 being filled with different dye solutions. Panels (b), (c) and (d) indicate lasing spectra emitted from C_1, C_2 and C_3 filled with Rhodamine 6G, 610 and 640 dye solutions, respectively.

3.5. Spacial overlap between evanescent wave of WGM and lasing gain

To explain the characteristic of the longer gain in an evanescent-wave pumped WGM fibre laser, the radial intensities of the WGMs in the used circular cavity and the evanescent field of pump light are calculated. For a TE wave in a cylindrical coordinate system shown in the top left of Fig. 1, the electric field of a WGM in a cylindrical cavity can be written as[15,17]

$$\boldsymbol{E}(r) = D_1 \left[\frac{n}{n_1^2 r} J_n(n_1 k_n^l r) \boldsymbol{e}_r - \frac{k_n^l}{n_1} J_n'(n_1 k_n^l r) \boldsymbol{e}_\varphi \right], \quad (0 \le r \le a) \tag{1}$$

$$\boldsymbol{E}(r) = D_2 \left[\frac{n}{n_2^2 r} H_n^{(1)}(n_2 k_n^l r) \boldsymbol{e}_r - \frac{k_n^l}{n_2} H_n^{'(1)}(n_2 k_n^l r) \boldsymbol{e}_\varphi \right], \quad (r \ge a), \tag{2}$$

where D_1 and D_2 are constants; a is the radius of the cavity; n_1 and n_2 are the refractive indexes of the cavity and its surrounding medium; J_n and $H_n^{(1)}$ are the nth Bessel and Hankel functions of the first kind, whose derivatives with respect to its argument are designated by the prime; k_n^l is the wave vector in vacuum for the nth angular mode number and lth radial mode order of WGM. For TM wave with radial mode number l and angular mode number n, the WGM is assigned by $\mathrm{TM}_n^l(l,\ n)$, while it is assigned by $\mathrm{TE}_n^l(l,\ n)$ for TE wave in this paper. Two lasing lines at the wavelengths of 591.59 and 589.43 nm in Fig. 3(b), which have been mode assigned[16,18] as TE_{1500}^1 and TE_{1490}^2, are chosen to calculate the distribution of radial intensity. Let $a = 98$ μm, $n_1 = 1.458$, and $n_2 = 1.395$, the radial intensities $I_{\mathrm{WGM}}(r)$ for the two WGMs are calculated and shown in Fig. 6.

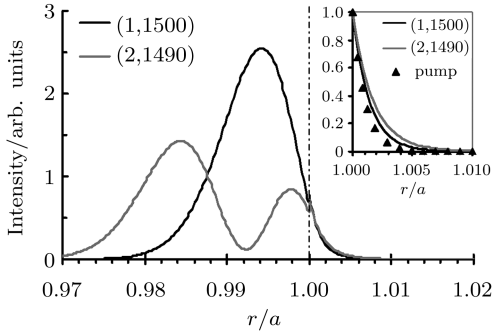


Fig. 6. Radial intensity distributions calculated for two WGMs assigned by $\mathrm{TE}_{1500}^1(1,\ 1500)$ and TE_{1490}^2 $(2,\ 1490)$, where the bumps at $r = a$ are caused by the discontinuity of TE wave, and the insert shows the intensities of evanescent waves for the pump light (solid triangles) and WGMs (black and grey curves).

The evanescence-wave intensity of the pump light is also calculated from[19]

$$I_{\mathrm{p}}(r) = I_0 \exp[-2k\beta(r/a - 1)a], \quad (r \ge a), \tag{3}$$

where $\beta = [n_1^2 \sin^2\theta / n_2^2 - 1]^{1/2}$, and $k = 2\pi n_2/\lambda_{\mathrm{p}}$. Letting $I_0 = 1$, $\theta = 86.8°$, $\lambda_{\mathrm{p}} = 532$ nm, the calculated result is shown in the insert of Fig. 6 by solid triangles, for a convenient comparison, the normalised evanescent-wave intensities of the modes TE_{1505}^1 and TE_{1490}^2 are also presented. The curves in the insert show clearly that in the radial direction of the cylindrical cavity ($r \ge a$), the intensity distributions of the two WGMs overlap well with the distribution of evanescence-wave of the pump light. Because the lasing gain in the evanescent-wave pumped WGM fibre laser is excited by the evanescent field of the pump light, the spatial distribution of the lasing gain is the same as that of the pump light. Therefore, it is reasonable to attribute the longer gain distance and the higher pumping efficiency in evanescent-wave pumped WGM fibre laser to the good spatial overlap between the lasing gain and the evanescent field of WGMs in a circular cavity.

4. Conclusions

For an evanescent-wave pumped and gain coupled WGM fibre laser, the dye gain is excited by the evanescent wave of the pumped light, distributed around the fibre and coupled into WGMs of a circular cavity. When the pump beam within the fibre is a meridian beam, there is no axial electric field of evanescent wave for the pump light, the WGM lasing emission from the fibre laser is a linearly polarised TE wave, while it is a mixed wave of the linearly polarised TE and TM waves when the pump beam is a skew beam within the fibre. Furthermore, a good spatial overlap between the dye gain and the evanescent fields of WGMs leads to a high pumping efficiency and a longer gain distance along the fibre, and linearly polarised three-colour lasing emissions from a single optical fibre can be realised by immersing the fibre into three different dye solutions, where may be found a potential application in multicolor display.

References

[1] Moon H J, Choung Y T and An K 2000 *Phys. Rev. Lett.* **85** 3161

[2] Kazes M, Lewis D Y, Ebenstein Y, Mokari T and Banin U 2002 *Adv. Mater.* **14** 317

[3] Moon H J, Park G W, Lee S B, An K and Lee J H 2004

Appl. Phys. Lett. **84** 4547
[4] Chen N K, Zhang L Y, Hsu K C, Hu L L, Chi S, Lai Y C, Tseng S M and Shy J T 2006 *Jpn. J. Appl. Phys.* **45** 6328
[5] Fujiwarra H and Sasaki K 1999 *Jpn. J. Appl. Phys.* **28** 5101
[6] Choi Y S, Moon H J, An K Y, Lee S B, Lee J H and Chang J S 2001 *J. Korean Phys. Soc.* **39** 928
[7] Li Y M, Liu Q, Tian X T and Zhang K S 2009 *Chin. Phys.* B **18** 2324
[8] Wu Y and Yang X 2001 *J. Phys.* B **34** 2281
[9] Shevchenko A, Lindfors K, Buchter S C and Kaivola M 2005 *Opt. Commun.* **245** 349
[10] Jiang X, Song Q, Xu L, Fu J and Tong L 2007 *Appl. Phys. Lett.* **90** 233501
[11] Monat C, Domachuk P and Eggleton B J 2007 *Nat. Photonics* **1** 106
[12] Ippen E P and Shank C V 1972 *Appl. Phys. Lett.* **21** 301
[13] Djafar K M and Lowell L S 2002 *Fibre-Optic Communications Technology* (Beijing: Science Press)
[14] Jackson J D 2001 *Classical Electrodynamics* (Beijing: Advanced Education Press)
[15] Pu X Y, Bai R, Xiang W L, Du F and Jiang N 2009 *Acta Phys. Sin.* **58** 3923 (in Chinese)
[16] Yang R, Yu W H, Bao Y, Zhang Y X and Pu X Y 2008 *Acta Phys. Sin.* **57** 6414 (in Chinese)
[17] Bohren C F and Huffman D R 1998 *Absorption and Scattering of Light by Small Particles* (New York: John Wiley & Sons, Inc.)
[18] Lam C C, Leung P Y and Yang K 1992 *JOSA* B **9** 1585
[19] Born M and Wolf E 1997 *Principles of Optics* (Cambridge: Cambridge University Press)