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Discussion on the Transmittance Characteristics of the 1152 nm Laser in Different Knot-Shaped Micro/Nano-Fiber Systems

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ABSTRACT

Four types of PM980 knot-shaped micro/nano-fiber systems were designed and researched on the 1152 nm beam transmission and modulation. The fiber's diameter was chosen at 822 nm so as to ensure the fundamental mode transmission. By means of the optical transmission matrix, the transmittance characteristics of 1152 nm laser generated from one single and two parallel knot-shaped micro/nano-fibers, as well as the two series knot-shaped and four-loop knot-shaped micro/nano-fiber systems were studied and simulated in detail. The results demonstrated that the longer the fibers were, the shorter oscillation period was. And as the numbers of micro/ nano-fibers increased, the light intensity transmittance became lower and the period arrays arrangements were more complex.

Keywords: Kont-shaped micro/nano-fiber systems, Transmittance characteristics, 1152nm laser.

1 Introduction

Nowadays, more and more optical devices were explored in the trends of miniaturization and integration. Micro/nano-optical devices had the characteristics of small volume, reliability, high coupling efficiency, flexibility, and so on [1-3]. For micro/nano-fibers, their diameters were almost smaller than the transmitted beams' wavelength. Compared with the common fibers, micro/nano-fibers were of lower loss, stronger evanescent fields and light confined ability, even higher dispersion non-linear effects [4,5]. Those micro/nano-fibers' advantages extremely promoted the development of many novel optical instruments, such as miniaturized optical fiber sensors, filters, resonators with high Q values, super-continuum spectrum, and so on [6,7]. In this article, the micro/nano-thoughts and methods were applied for 1152 nm laser micro/nano-resonators design. The 1.15 µm light could be produced by LD-pumped Yb^{3+}-doped fiber lasers and Raman fiber lasers, diode lasers, et al., which could be applied as pumping sources for Ho^{3+}-doped mediums and fundamental beams of yellower lights [8,9].

However, all of them were big size instruments, and hadn't been connected with micro/nano-optical devices. In this manuscript, four types of micro/nano-knot-fiber resonators were discussed for the 1152nm light transmission, including one loop knot fiber, two parallel micro/nano-knot-fiber devices, the series micro/nano-knot-fiber and four knot fiber resonators. When the micro/nano-fibers' diameters was 822nm, which met with the need of the fundamental model transmission. The more the micro/nano-loops were, the lower the transmittance was, and the models output more complexly. The calculated and simulated results would provide the references for further research and applications for micro/nano-equipments at 1152 nm.

2 Experimental schemes

Three kinds of micro/nano-fiber resonators were usually used in optical modulating, filter and sensors, i.e., loop resonators, knot resonators and coil resonators. Here, the second one was adopted to analyze the transmittance characteristics at 1152nm. As illustrated in Fig.1, the knot-shaped micro/nano-fibers had one coupling zone. When the amplitude of the input light was $E_{1,}$ which was divided as two parts, one was E_3, the other was E_{41}. As E_3 transmitted to the coupling zone along the fiber loop, the amplitude was E_2. The transmission coefficient was β. E_2 was also was divided into two parts, one was E_{42}, the another was coupled into the loop again. Finally, the whole loop micro/nano-fiber would output the light E_4. E_4 was the sum of E_{41} and E_{42}. Here, it was assumed that the light was not reflected from the output end.

According to the matrix of lights traveling in the knot-shaped fiber, the expressions of E_3 and E_4 were listed as follows [10]:

$$\begin{bmatrix}E_3\\ E_4\end{bmatrix} = (1-r_0)^{1/2}\begin{bmatrix}\sqrt{1-k} & i\sqrt{k}\\ i\sqrt{k} & \sqrt{1-k}\end{bmatrix}\begin{bmatrix}E_1\\ E_2\end{bmatrix} \qquad (1)$$

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$$E_2 = E_3 \exp(i\beta L) \tag{2}$$

$$\mathrm{E}_3 = \frac{\sqrt{(1-k)(1-r_0)}}{1-i\sqrt{k(1-r_0)}\exp(i\beta \mathrm{L})}\mathrm{E}_1 \tag{3}$$

$$\mathrm{E}_4 = \left[\begin{array}{l} i\sqrt{k(1-r_0)} \\ +\dfrac{(1-k)(1-r_0)\exp(i\beta \mathrm{L})}{1-i\sqrt{k(1-r_0)}\exp(i\beta \mathrm{L})} \end{array}\right]\mathrm{E}_1 \tag{4}$$

Where, L was the fiber length, r_0 was the coupling efficient, k was the beam divided ratio, β was the transmission coefficient, which was related with the light's wavelength. The fiber's core index n_1, the clad index was n_2, and the diameter D, as stated in the following expressions.

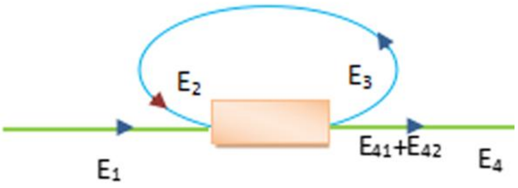


Fig.1 The diagram of single knot-shaped micro-nano-fiber system

$$\beta = \frac{2\pi}{\lambda} + \frac{\gamma^2\lambda}{4\pi} \tag{5}$$

$$\gamma = \frac{2.246}{D}\exp\left[\frac{n_1^2+n_2^2}{8n_2^2} - \frac{n_1^2+n_2^2}{n_2^2(n_1^2-n_2^2)^2}\frac{\lambda}{(\pi D)^2}\right] \tag{6}$$

Here, a PM 980 fiber was taken as 1152 nm laser transmission medium. The values of n_1 and n_2 were 1.4668 and 1, respectively. The variation of β and diameter D was obtained as Fig.2. When the fiber's diameter was from 600 nm to 1400 nm, β was high, especially at 850 nm, β was the maximum value at 5.98.

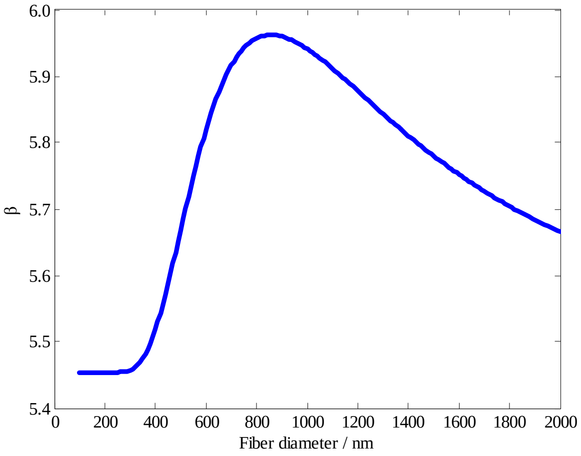


Fig.2 The relationship with fiber diameter and β

In order to achieve fundamental model transmission, it was essential to consider the fiber's diameter according to the normalized frequency parameter V, that was,

$$V = 2\pi\rho(n_1^2 - n_2^2)^{1/2}/\lambda_0 \le 2.405 \tag{7}$$

Where ρ was the fiber's radius. λ_0 was the wavelength in freedom space. By means of calculation, the fiber's diameter D was less than 852nm so as to ensure the fundamental model oscillation. Therefore, the diameter was set as 822nm in the following simulations and calculations process which would ensure both fundamental mode and large β value.

2.1 The output of one knot-shaped micro/nano-fiber system

Firstly, the transmission characteristic of one knot-shaped micro/nano-fiber was discussed. According to the expressions above, the transmittance T could be deduced was:

$$T = \frac{|E_4|^2}{|E_1|^2} = \left\|\left[i\sqrt{k(1-r_0)} + \frac{(1-k)(1-r_0)\exp(i\beta L)}{1-i\sqrt{k(1-r_0)}\exp(i\beta L)}\right]\right\|^2 \tag{8}$$

It could be seen that the fiber length L, the coupling efficient r_0, the beam divided ratio k and the diameter D were the influence factors of the transmission T. T was varied periodically with the fiber length L obviously, but it was almost no changes along with the fiber diameter D.

2.2 The output of two parallel knot-shaped micro/nano- fibers system

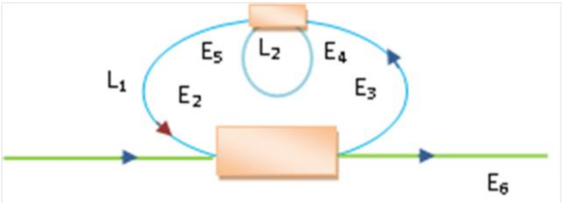


Fig.3 The diagram of the parallel micro/nano-fibers system

Based on the research on the above mentioned, two parallel loop fibers were shown in Fig. 3. In this system, the small loop fiber's length was L_2, and the long fiber's was L_1。The optical transmission matrix in the small loop fiber was T_2, and the final output light was E_7 that was decided by L_1, L_2, k_1, k_2, r_1 and r_2.

$$T_2 = i\sqrt{k_2(1-r_2)} + \frac{(1-k_2)(1-r_2)\exp(i\beta L_2)}{1-i\sqrt{k_2(1-r_2)}\exp(i\beta L_2)} \tag{9}$$

$$\begin{aligned}\mathrm{E}_7 &= i\sqrt{k_1(1-r_1)}E_4 \\ &+ \frac{(1-k_1)(1-r_1)\mathrm{T}_2\exp[\mathrm{i}\beta(L_1+L_2)]}{1-i\sqrt{k_1(1-r_1)}\mathrm{T}_2\exp[\mathrm{i}\beta(L_1+L_2)]}E_4\end{aligned} \tag{10}$$

2.3 The output of two series knot-shaped micro/nano-fibers system

In Fig. 4, two micro/nano-fibers were consisted of the series system, where the first fiber's output optical field was the input field of the second micro/nano-fiber, thus the equations (1)-(4) and (8) were used twice in such configuration.

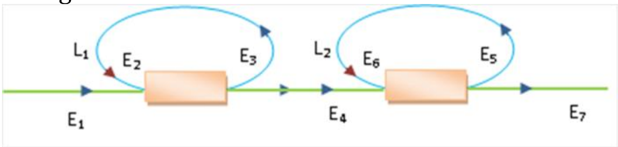


Fig.4 The diagram of two series micro/nano-fibers system

2.4 The output of four knot-shaped micro/nano-fibers system

Finally, the characteristics of the four knot-shaped micro/nano-fiber system, including two long fiber loops and two short fiber loops knot-shaped configuration, was simulated and calculated, as shown in Fig.5. This model was more complicated than those designed above, and all the previous calculated results should be applied.

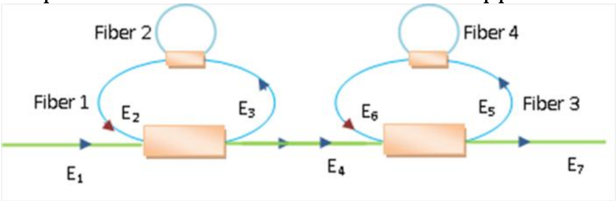


Fig.5 The diagram of four knot-shaped micro/nano-fiber system

3 Results and Discussion

As established in the preliminary analysis, the output characteristics of above micro/nano-fiber models were discussed as follows.

For one knot-shaped micro/nano-fiber system, when r_0=10 % and k=80 %, the relationship of transmittance T with the fiber length L and diameter D was shown in Fig.6. In order to further verify the actual conditions, the fiber length L was fixed at 500 nm, 20 μm and 350 μm respectively, the fiber length D influenced the transmittance as shown in Fig. 7. The longer the fiber was, the more periods there were, even there were no lights output or the periods were quite small. Therefore, too long and too short micro/nano-fibers were not good enough for light operation.

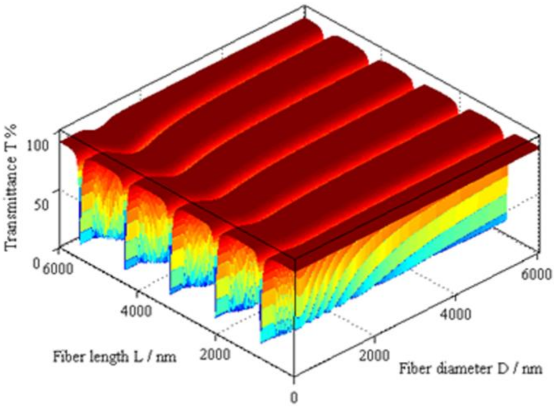


Fig.6 The influence of fiber diameter and fiber length on the transmittance

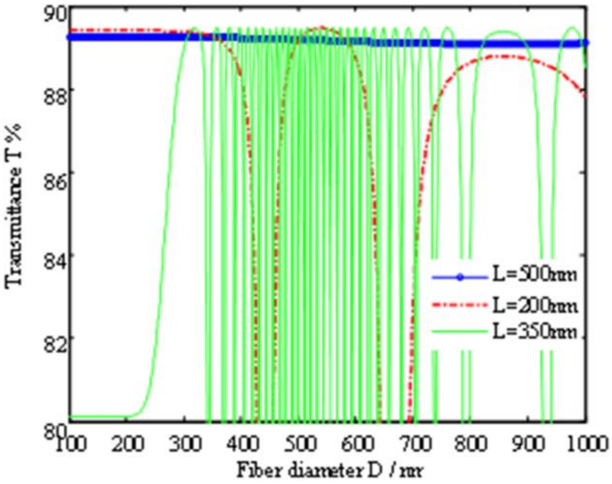


Fig. 7 The transmittance versus the fiber diameter

According to Fig. 7, when the diameter was 588nm, the three different length fibers were of almost the same output.

The transmittance T was described in Fig.8 as the fiber's length was set as 20μm. Some length values would not be chosen during the course of manufacture to ensure the transmittance.

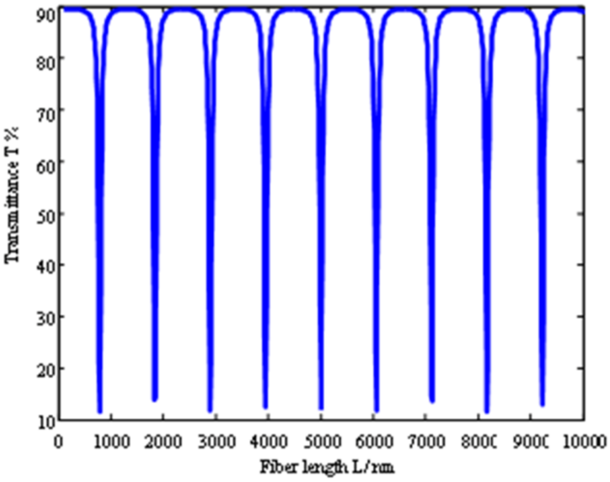
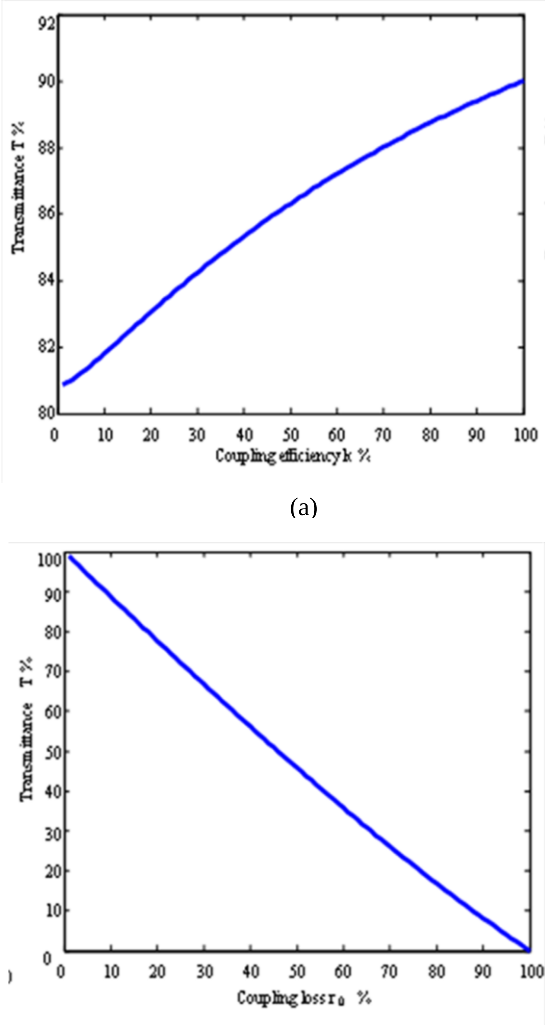


Fig. 8 The transmittance versus the fiber length

Besides the fiber length L and the diameter D, the coupling efficiency k and the coupling loss r_0 were also important factors for the micro/nano-knot fiber loop. Fig.9 (a) and Fig. 9 (b) demonstrated the changing laws. They were both almost linear influences for the output.

For the output of two parallel knot-shaped micro/nano- fibers system, by the functions of (9) and (10), the output transmittance could be calculated and the influence factors could be analyzed. In Fig.10, both the long fiber and the small fiber were the modulators for the laser beam. The periods in L_1 direction was longer than in the L_2 direction. L_1 and L_2 were individual values to meet with high transmittance.



(a)

(b)

Fig.9 The transmittance versus the coupling efficiency and the coupling loss

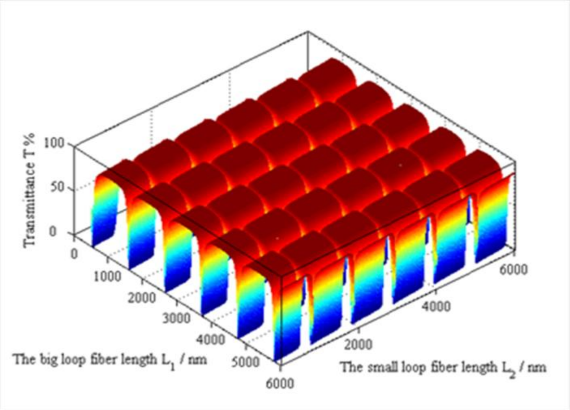


Fig.10 The influence of different fiber lengths on the system transmittance

According to Fig.10, the long fiber and the small fiber length were chosen as 2029nm and 570nm, respectively. For the coupling loss (in Fig.11), the long loop fiber's r_{01} made transmittance T changed obviously, while the short loop fiber's r_{02} smoothly, which was beneficial for operation.

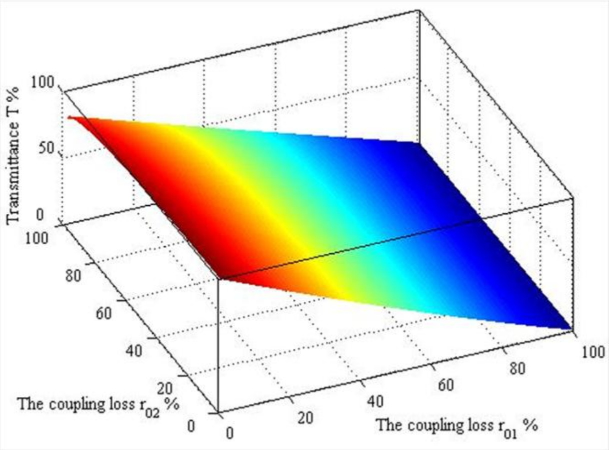


Fig.11 The coupling loss versus the transmittance

Fig.12 showed the beam divided ratio of two parts. The long fiber loop fiber's beam divided ratio $k_{01}$was the main factor influencing the transmittance T, relatively, $k_{02}$was not as important as k_{01}.

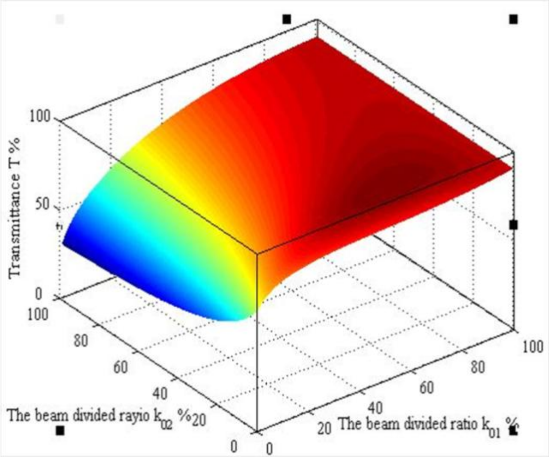


Fig.12 The beam divided ratio versus the transmittance

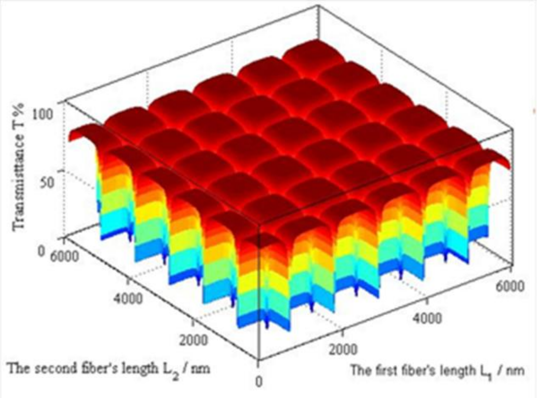


Fig.13 The fibers' lengths versus the transmittance in the series system

According to the analysis above, it could been seen that the long micro/nano-fiber was the main part in the parallel system, though the short micro/nano-fiber like as the long fiber was of the characteristics of modulating 1152nm light beam, especially its length L_1 influencing the output obviously, however the coupling loss and the beam divided ratio were slight influence on the output.

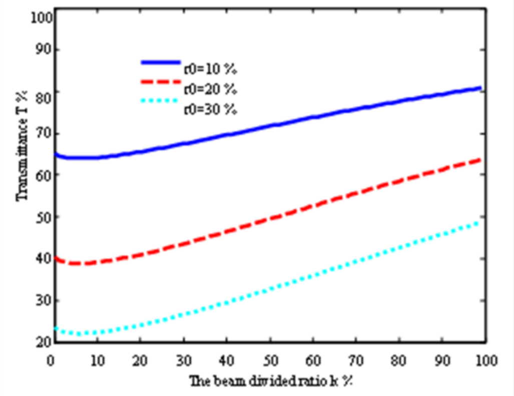


Fig.14 The transmittance versus the beam divided ratio

For the two series knot-shaped micro/nano-fibers system, how about the output vs. the fiber length, the coupling coefficient and the beam divided ratio? According to the theoretical analysis, the results demonstrated in Fig.13 and Fig.14. The periods in the L_1 and L_2 directions were the same and longer than the parallel system's. The higher the beam divided ratio *k* was, the higher the transmittance was.

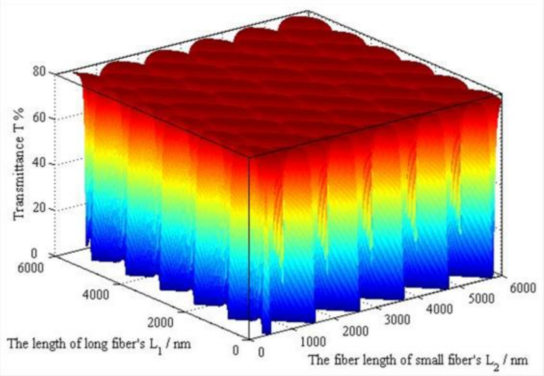


Fig.15 The transmittance versus the long and small fibers' lengths

For the four knot-shaped micro/nano-fibers system, there were two conditions to be discussed. One was that the two parallel micro/nano-fibers' lengths were not identical, that was, both the fiber 1 and fiber 3 were the same length L_1, while the fiber 2 and fiber 4 were the same length L_2, the transmittance *T* of this system was shown in Fig.15. It was periodic arrays, while the direction was not in the x- or y-axis, but along with diagonal direction. The other was that fiber 1 and fiber 2 were of the same length L_3, fiber 3 and fiber 4 were of the same length L_4.

The simulated results of transmittance *T* was shown in Fig.16. Differently from the former, the periodic arrays here were in the direction of x- and y-axis, Worthy mentioning was that dual-periods configurations. It demonstrated that the more micro/nano- fiber loops, the 1152 nm laser was modulated complexly.

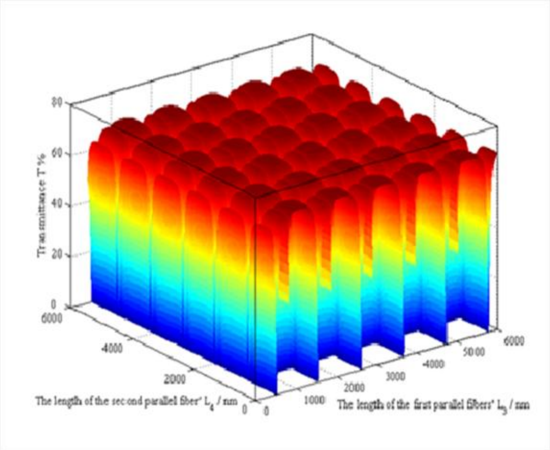


Fig.16 The transmittance versus the parallel and series fibers' lengths

4 Conclusions

In conclusion, several kinds of knot-shaped micro/nano- fibers including the single knot fiber, two parallel knot fibers, two series knot fibers and four knot fibers system were all discussed on the modulation for the 1152 nm laser. The fiber's diameter was 822 nm in order to ensure the fundamental model transmission. Each transmittance *T* was demonstrated in these configurations, which was beneficial for the 1152 nm laser instruments and applications in future.

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