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To cite this article: HU Qinggui and MU Yining 2018 J. Phys. Commun. 2 035018

View the article online for updates and enhancements.
The influence of vibration on spatial coupler and the tapered receiver

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Keywords: tapered structure, vibration, coupling efficiency, optical receiver

Abstract
In order to analyze the loss of the free-space optical receiver caused by the vibration, we set up the coordinate systems on both the receiving lens surface and the receiving fiber surface respectively. Then, with Gauss optics theory, the coupling efficiency equation is obtained. The solution is calculated out with MATLAB software. To lower the impact of the vibration, the directional tapered communication fiber receiver is proposed out. In the next step, the sample was produced and two experiments were done. The first experiment shows the coupling efficiency of the new receiver is higher than that of the traditional one. The second experiment shows the bit error rate of the new receiver is lower. Both of the two experiments show the new receiver could improve the receiving system’s tolerance with the vibration.

1. Introduction

Due to the inherent advantages including a huge license free-spectrum, high security and so on, free-space optical (FSO) communication systems have confirmed to be a strong alternative to radio-frequency systems. Since the common optical fiber communication technology is becoming more and more widely used, the combination of the two technologies is a recognized trend. For the combination, the effective couple of light-into-fiber is the key problem. Especially in some vibration environments, it is even true.

For FSO communication systems, the vibrations will produce fluctuations in both the intensity and the phase of the received signal [1]. Over the past decade, many authors have studied this problem and lots of methods have been proposed [2–9]. In [2], a pointing error model of the vibration was proposed. In [3], an other pointing error model was proposed considering a nonzero boresight error at the receiver for independent identical Gaussian distributions. In [4], it put forward the adaptive optics correction method to improve the coupling efficiency under the vibration environment. On the whole, most of those studies focus on the cylindrical optical fiber receiver. The literatures about the tapered fiber receiver are relatively fewer.

On the other hand, in some areas (e.g., quantum physics, biological sensing, photonics, etc), tapered optical fibers (TOFs) are very powerful tools [10, 11]. In [11], the fabrication and performance of a MOSFET-like silicon light source that is able to monolithically integrate with silicon photo-detector in standard 3 μm CMOS process technology is introduced. Those former works show it’s possible for TOFs to be adopted in the FSO communication systems. In our previous work [12], in order to study the coupling characteristics of TOFs in space communication system, the theoretical model of the power distribution of the new connector is established. The longitudinal propagation constant of the taper connector is expanded by Taylor series according to the wave theory. And the approximate solution of the power distribution is obtained. In this work, we set up the coordinate systems on both the receiving lens surface and the receiving fiber surface to study the coupling characteristics. In the next step, we put forward the compensation method and do two experiments to test its performance.
2. The influence of the vibration on the coupling efficiency

As shown in figure 1, it is the traditional coupling system. Because the fiber is too small, the lens system requires high imaging precision.

We assume the laser beam belongs to Gauss beam after it passes through the space. Then, we can analyze the coupling efficiency with geometrical optic method. As shown in figure 2, the light is focused into the fiber by the lens. Due to the vibration of the laser transmitting platform, both the axial deviation ($\Delta z$) and lateral deviation ($\Delta x$) appear on the receiving surface, where the incidence angle is $i$.

As shown in figure 3, The radius of receiving fiber is $r$. We assume the received light spot is a circle, whose radius is $R$. The center distance between the fiber and the light spot is $\Delta r$. Figure 3(a) is the situation of that $0 < \Delta r < r - R$, while figure 3(b) is the situation of $R - r < \Delta r < r + R$, in this case, we could divide the light spot into two parts, as shown in figure 3(c).

In order to analyze the coupling efficiency, the coordinate systems are set up on both the receiving lens surface and the receiving fiber surface. As shown in figure 4.

We suppose the light is parallel with principal axis, the incident light intensity at the front surface of the lens is $I_{in}$. The incident angle is $\theta_1$, refraction angle $\theta_2$, the refractive index of the air is $n_1$, the refractive index of the fiber core is $n_2$. Then, on the fiber surface, the reflectivity $R_i$ and the reflection coefficient $r_i$ are given by the following equations [13],

$$R_i = r_i^2$$

$$r_i = \frac{n_1 \cos \theta_1 - n_2 \cos \theta_2}{n_1 \cos \theta_1 + n_2 \cos \theta_2}$$

When the receiving fiber surface is in the superposition with the focal plane of the lens, on the condition of $0 \leq i < \arctan (r/f)$, $\theta_1$ meets the following equation [14]:

$$\tan \theta_1 = \frac{(x - f \tan \theta_2)^2 + y^2)^{\frac{1}{2}}}{f}$$

Figure 1. The traditional coupling system.

Figure 2. The axial deviation and lateral deviation produced by vibration.

Figure 3. The locations of the light spot and fiber core.

Figure 4.
According to Snell theory \([12–14]\), we can gain the following equation.

\[
n_1 \sin \theta_1 = n_2 \sin \theta_2
\]

Then, we can deduce the following two equations:

\[
n_2 \cos \theta_2 = (n_2^2 - n_1^2 \sin^2 \theta_1)^{\frac{1}{2}}
\]

\[
n_1 \cos \theta_2 = \frac{n_2}{n_1}(n_2^2 - n_1^2 \sin^2 \theta_1)^{\frac{1}{2}}
\]

With above equations, the following formula could be derived.

\[
R_i = \left[ \frac{n_1 \cos \theta_1 - (n_2^2 - n_1^2 \sin^2 \theta_1)^{\frac{1}{2}}}{n_1 \cos \theta_1 + (n_2^2 - n_1^2 \sin^2 \theta_1)^{\frac{1}{2}}} \right]^2
\]

\[
= \left[ \frac{n_1 \sqrt{(x - f \tan i)^2 + y^2 + f^2}}{n_1 \sqrt{(x - f \tan i)^2 + y^2 + f^2} + \sqrt{n_2^2 - (x - f \tan i)^2 + y^2 + f^2}} \right]^2
\]

\[
= \left[ \frac{n_1 f - \sqrt{n_2^2((x - f \tan i)^2 + y^2 + f^2) - n_1^2((x - f \tan i)^2 + y^2)}}{n_1 f + \sqrt{n_2^2((x - f \tan i)^2 + y^2 + f^2) - n_1^2((x - f \tan i)^2 + y^2)}} \right]^2
\]

When the receiving fiber surface is NOT in the superposition with the focal plane of the lens, according to geometry relation, \((x', y')\) and \((x, y)\) meet the following equation.

\[
x' = -\frac{\Delta z}{f} x + (f + \Delta z) \times i
\]

\[
y' = -\frac{\Delta z}{f} y
\]

At last, we can gain the following coupling efficiency equation.

\[
\eta = \begin{cases} 
1 - \frac{\iiint_{\Sigma_1} I_{in} R_i dx' dy'}{\iiint_{\Sigma_1} I_{in} dx' dy'}, & 0 \leq \Delta r < r - R, \Delta Z < \frac{2f}{D} \\
\iiint_{\Sigma_1+\Sigma_2} I_{in} dx' dy' - \iiint_{\Sigma_1} I_{in} R_i dx' dy' - \iiint_{\Sigma_2} I_{in} dx' dy', & r - R \leq \Delta r < r + R, \Delta Z < \frac{2f}{D} \\
0, & \Delta r \geq r + R, \Delta Z < \frac{2f}{D}
\end{cases}
\]

With above equation, after some parameters are given, we can analyse the relationship between \(\eta\) and \(i\). For example, on the condition of \(0 < \Delta z \leq (2f/\text{D}) \times r\), to suppose \(r\) is 25 \(\mu\)m, NA is 0.22, \(f\) is 50 mm, \(D\) is 20 mm,
Δz is 100 μm, then, with MATLAB software, the relationship between η and i could be calculated out, which is shown in figure 5. From figure 5, we can see that, when i is less than 0.2 mrad, η falls slowly. Specifically, when i increases from 0 to 0.2 mrad, η falls from 91% to about 87%. After that, η falls quickly. When i increases from 0.2 mrad to 1 mrad, η falls from 87% to about 30%. From the figure, we can see that, i has great influence on η.

3. The tapered receiver

3.1. The traditional optical fiber coupling system and new coupling model
As shown in figure 6, it is the new coupling system, in which the tapered fiber receiver is adopted. Compared with the common receiver, the tapered fiber receiver has larger light receiving area, it could improve the coupling efficiency.

3.2. The theoretical analysis on the coupling efficiency
Compared with the common receiver, the new receiver’s radius is 35 μm. Other parameters are same (i.e., NA is 0.22, f is 50 mm, D is 20 mm, Δz is 100 μm etc). Then, we could calculate the efficiencies of both the common and new receivers, as shown in figure 7 (where η₁ is the efficiency of the common receiver, η₂ is the efficiency of the new).

From figure 7, we can see that, both η₁ and η₂ decrease gradually. But η₂ decrease relatively slower. In other word, η₂ is higher than η₁, it indicates the performance of the new receiver it better.

4. The experiments

4.1. The manufacturing process of the sample
In our previous work, we have made out the tapered fiber connector [12, 15]. At this time, we adopt the same method to manufacture the sample of the new receiver. Namely, the large-mode-area (LMA) fiber is reformed with the fused taper technique. We use SCS-4000 fused taper system to do the work. In the process of fusing, the
LMA fiber is fused with other common fiber. The oxyhydrogen flame is adopted as fusing flame. The range of the fusing flame is set at about 7 mm. The nanoscale quartz powders are adopted as the binder.

After the two fibers are fused together, the tapered structure appears at the junction. We use the fiber cutting knife to cut the junction to gain the tapered head. Then, we use the wheel type optical fiber polishing machine to polish the head. For the polishing machine, its grinding accuracy is better than 1 μm. Finally, the sample is ready. Its cone bottom diameter is 70 μm, half cone angles is 8°, \( n_1 \) is about 1.49 and \( n_2 \) is about 1.46.

For the new tapered receiver, in our previous work, it is introduced the taper angle should be restricted by the following formula \[12, 15\].

\[
\alpha \leq 90° - \arcsin(n_2/n_1)
\]

In this experiment,

\[
\alpha \leq 90° - \arcsin(n_2/n_1) \\
= 90° - \arcsin(1.46/1.49) = 90° - 78° = 12°
\]

Then, the taper angle of the sample meets the demand.

4.2. The coupling efficiency experiment

Here, we adopt the experiment platform which has been used in our previous work \[12\]. As shown in figure 8, the tip/tilt mirror is installed at position A. It is controlled by the control system so that it could simulate the different frequencies and amplitudes. In this experiment, the output power of the light source laser is set up to 1 mW.

Firstly, the tip/tilt mirror does not work. We adjust the fixtures to ensure the best alignment of the two fibers. In this condition, the received optical power is maximum. For the traditional connector, the received maximum optical power (at the position B) is 0.70 mW. For the new tapered connector, the received maximum optical power is 0.68 mW. It shows the coupling efficiency of the new tapered is slightly lower. The reason is that
the weld joint of the tapered connector causes little optical energy loss. In the experiment, this tiny difference is ignored.

Considering that our testing equipments including the control system and bit error rate tester work more stable in 40 Hz and 80 Hz. So, we choose those frequencies to do the experiment. For the traditional connector, if the received optical power is $P_1$, its coupling efficiency $\eta_1 = P_1 / 0.7 \text{ mW}$. Similarly, for the new tapered connector, if the received optical power is $P_2$, its coupling efficiency $\eta_2 = P_2 / 0.68 \text{ mW}$. The experimental results are shown in figures 9 and 10.

Figure 9 shows the relationship between $\eta_1$ and $\eta_2$ in the frequency of 40 Hz. From the figure, we can see that when the amplitude increase, both $\eta_1$ and $\eta_2$ decrease. But compared with $\eta_2$, $\eta_1$ decreases more rapidly. For example, when the amplitude is 50 $\mu$rad, $\eta_1$ is about 85%, $\eta_2$ is about 88%. When the amplitude increases to 300 $\mu$rad, $\eta_1$ reduces to about 15%, but $\eta_2$ reduces to about 55%.

The rotated tip/tilt mirror is used to simulate the vibration environment. It will produce the displacement for the receiver. The experiment result shows the tapered structure could improve the connector’s tolerance with the displacement.

When the frequency is 80 Hz, as shown in figure 10, the similar conclusions could be drawn.

When comparing figure 9 with figure 10, We can’t find obvious difference between them. It indicates the optical power coupling efficiency is affected mainly by the amplitude, it is affected little by the frequency.
4.3. The error rate measurement experiment

In this experiment, bit error rate tester (BERT) is installed in the above experiment platform (as shown in figure 8). The basic principle of BERT is transmission data and then receiving it to get the error rate. This technology has developed very mature. Its output is connected to the position A, while the input is connected to the position B. In the experiment, we choose CMR-2048V BERT to do the experiment, which is the product of Beijing Wangyuan Communication Limited Company. Its input sensitivity is from 0 dB to $-43$ dB. The bit rate of the digital signal is 2048 Kbps. The coding mode is HDB3.

Firstly, the common connector is installed in the fixture. The frequency is set to 40 Hz, the amplitude is set to $50 \mu$rad. Then, the error rate test experiment starts. The test time lasts 2 min. The test data is about $1.2 \times 10^{10}$ bit. After the result is obtained. The amplitude is set to 100 $\mu$rad, 150 $\mu$rad, 200 $\mu$rad, 250 $\mu$rad, 300 $\mu$rad respectively to do the experiment in order.

Later, the frequency is set to 80 Hz to do the experiment again. After the experiment of common connector is finished, the new connector is installed in the fixture to do the experiment once more. The final results are shown in figures 11 and 12.

From figure 11 we can see that, bit error rate (BER) of common receiver is higher than that of the new receiver always. This point can be seen from figure 12 also.
When comparing figure 11 with figure 12, we can discover that high frequency is corresponding to high error rate. For example, when amplitude is 300 μrad, in figure 11 (where frequency is 40 Hz), BERs of new and common receiver are 0.10 and 0.23 respectively. While in figure 12 (where frequency is 80 Hz), they are 0.15 and 0.33 respectively. It shows frequency could affect the experimental result.

While in the former experiment, the experimental result is affected mainly by the amplitude only, and it is affected little by the frequency. This is because the vibration frequency could change the mode of laser transmission, which can produce obvious influence on the Optical transmission mode, but has little influence on the coupling efficiency of the optical power.

5. The conclusion

With the establishment of coordinate systems on both the receiving lens surface and the receiving fiber surface respectively, the coupling efficiency equation is obtained to study the influence of the vibration. Then, the directional tapered fiber receiver is proposed out. Later, the sample was made successfully and two experiments in the micro vibration environment were done. The first experiment shows the tapered structure could improve the connector’s tolerance with the vibration. The second experiment shows the bit error rate of the new receiver is lower, which indicates the new receiver performs better. In addition, the first experiment shows the optical power coupling efficiency is mainly affected by the amplitude, and it is affected little by the frequency. While, the second experiment shows both the amplitude and frequency could affect the bit error rate.

Acknowledgments

The author would like to show the gratitude to Mr WANG Jun and LI Yang, the technicians of Chengdu SEI Optical Fiber Corporation, who have provided the experimental facilities and the manufacturing technical support. The author HU Qinggui also acknowledges the financial support from The National Natural Science Foundation of China (Grant No.61275080); 2017 Jilin Province Science and Technology Development Plan-Science and Technology Innovation Fund for Small and Medium Enterprises (20170308029HJ); ‘thirteen five’ science and technology research project of the Department of Education of Jilin 2016 (16J009).

Special note

Project has been authorized Chinese Patent, the name of the patent: ‘The directional multimode optical fiber with tapered plug’; patent application number: CN201620005088.0; public notice number: CN205301623U.

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