Diffraction Calculation of Waveguide Propagation Turning Coupling

Feng Xianghua
College of Science
Information Engineering University
Zhengzhou, China
Fengxianghua2002@hotmail.com

Ji Jiarong
College of Optoelectronic Science and Engineering
National University of Defense Technology
Changsha, China
1465770025@qq.com

Zhang hui
College of Science
Information Engineering University
Zhengzhou, China
1456220792@qq.com

Wen changli
Key Laboratory of Astronautic Dynamics
Satellite Control Center
Xian, China
Wc1100@163.com

Abstract—The VCSEL light transmission module, whose array was 12 spacing 250μm laser launcher, combine 12 array waveguide belts and the receive module to form the parallel optical interconnection. For achieving an efficient optical interconnection, how to make the light coupling pass in/out waveguide has become an important work. The micro optical steering coupler, which is composed of micro-lens arrays and miniature right-angle prisms, could reduce the loss in optical transmission, improve the light 900 turning coupling efficiency, and reduce the spatial volume effectively. Here, a method using Collins formula was put forward, aiming to analyze prism couple and waveguide propagation 900 turning coupling; meanwhile, the optical performance of the micro optical steering coupler based on this method was analyzed. The simulation results indicate that micro coupler can enhances the efficiency of optical transmission and turning coupling.

Keywords- micro-lens arrays; right-angle prisms; light 90^0 turning coupling; Collins formula; Diffraction calculation

I. INTRODUCTION

With the development of high speed optical interconnection[1~3]technique, optical waveguide[4~7] have been playing a very important role in the development of integrated optics. The VCSEL light transmission module, whose array has 12 laser launchers with 250μm spacing, has been widely applied in the commercial field. These components combine 12 array waveguide belts and the receive module to form the parallel optical interconnection. With a view to accomplishing an efficient optical interconnection, how to make the light coupling pass in/out waveguide has become a significant work. In this work, the beam from VCSEL array can be coupled in waveguide and the light from waveguide can be coupled out to detector (Fig.1). Several common coupling steering methods are 450 reflectors[8,9], binary optical device[10,11] and waveguide grating coupler. The waveguide grating coupler[12~14] which makes a grating device directly on the waveguide achieves an advantage in reducing the size and weight of optical system.

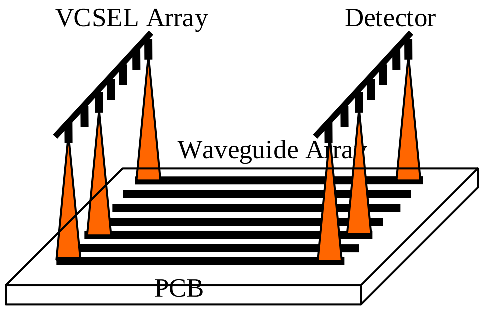
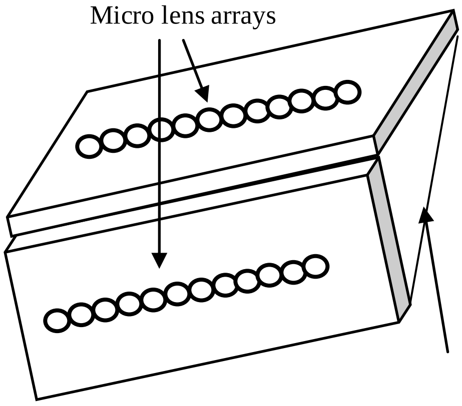
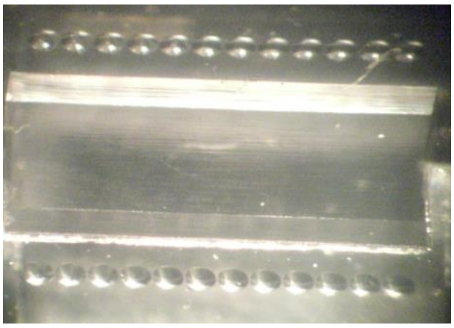


Figure 1. The schematic view of vertically couple and focusing light



(a)



(b)

Figure 2. (a) The sketch map of MOSC (b) The real photos of MOSC

As the sketch map and real photos of the micro optical steering coupler (MOSC) are shown in Fig.2, MOSC is composed of micro lens arrays (Plano convex lens) and miniature rectangular prisms. The entire space size of MOSC is 2.6mm×6.4mm×0.8mm with the lens diameter in micro-lens arrays of 250μm and the arrays interval of 250μm. The slope of right-angle prism was plated with gold reflective film, whose intensity reflectivity is up to 99%. The optical transmission loss in this component is very low.

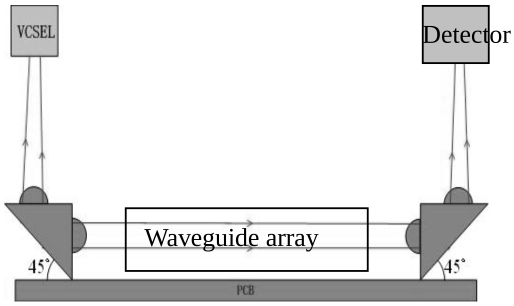


Figure 3. The schematic diagram of optical coupling steering

The principle of optical coupling steering by MOSC is shown in Fig.3. Light from VCSEL array or waveguide array was focused and collimated by the first micro-lens arrays, and then a 900 turn was accomplished by the total reflection of the micro right angle prism. Finally, light arrive to the waveguide array or detector array through the second micro-lens arrays.

Therefore, MOSC could reduce the loss in optical transmission, improve the light 900 turning coupling efficiency, reduce the spatial volume effectively, and integrate waveguides and electronic components to form photoelectric systems. Here, a method using Collins formula was put forward, aiming to analyze prism couple and waveguide propagation 900 turning coupling; meanwhile, the optical performance of MOSC based on this method was analyzed. The simulation results indicate that micro-component can enhances the efficiency of both optical transmission and turning coupling.

II. THE PARAXIAL OPTICAL SYSTEM AND COLLINS FORMULA

According to the matrix optical theory[15], the optical characteristics of an axisymmetric paraxial optical system can be described by a 2×2 matrix $\begin{bmatrix} A & B \\ C & D \end{bmatrix}$.

The common optical system in geometric optics is usually composed of lens, reflection mirror, interface between two different media, homogeneous or inhomogeneous medium etc. As long as we can simulate the track of a paraxial ray, the performance of the optical system could be confirmed.

Let z axis is the optical axis of an optical system, the intersection of the simulated light and the z plane is (x1, yl) in z = z1 plane. The tangent direction cosine of light are α1, β1 and $\sqrt{1-\alpha_1^2-\beta_1^2}$. In the input plane z = z1 and the output plane z = z2, these parameters can be written in the form of two column matrices, respectively, which are $\begin{bmatrix} x_1 \\ y_1 \\ \alpha_1 \\ \beta_1 \end{bmatrix}$ (the input plane) and $\begin{bmatrix} x_2 \\ y_2 \\ \alpha_2 \\ \beta_2 \end{bmatrix}$ (the output plane).

In geometry optics, the transformation of paraxial light by paraxial systems satisfies linear approximation. While propagating from the input plane z = z1 to the output plane z = z2, the conversion of light ray by the optical systems between the two planes can be expressed as:

$$\begin{bmatrix} x_2 \\ y_2 \\ \alpha_2 \\ \beta_2 \end{bmatrix} = \begin{bmatrix} a_{11} & a_{12} & b_{11} & b_{12} \\ a_{21} & a_{22} & b_{21} & b_{22} \\ c_{11} & c_{12} & d_{11} & d_{12} \\ c_{21} & c_{22} & d_{21} & d_{22} \end{bmatrix} \begin{bmatrix} x_1 \\ y_1 \\ \alpha_1 \\ \beta_1 \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \begin{bmatrix} x_1 \\ y_1 \\ \alpha_1 \\ \beta_1 \end{bmatrix} \quad (1)$$

where A, B, C, D represent the 2×2 matrix expressed by the corresponding lowercase letters, respectively.

As shown by the upper formula, in general paraxial optical systems, the output light parameter is the transformation of the input light parameter by a 4×4 matrix M through linear approximation. M is called the transformation matrix of optical system.

Every optical component or the transmission medium between components can be regarded as a simple sub-optical system; all of them have their corresponding transformation matrix. When an optical system is composed of N components, the transformation matrix of the whole system can be express as:

$$\begin{aligned} M &= M_N \Lambda\ M_2 M_1 \\ &= \begin{bmatrix} A_N & B_N \\ C_N & D_N \end{bmatrix} \Lambda \begin{bmatrix} A_2 & B_2 \\ C_2 & D_2 \end{bmatrix} \begin{bmatrix} A_1 & B_1 \\ C_1 & D_1 \end{bmatrix} \end{aligned} \quad (2)$$

The transformation matrix of every common optical component can be easily set up in accordance to ray tracing and paraxial geometrical optical theory.

Extending from Fresnel theory of diffraction approximation, combined with the matrix optics, Collins derived Fresnel diffraction formula of axisymmetric paraxial system – Collins formula, which established the mathematics relation between the matrix element ABCD of axial symmetric paraxial systems and the diffraction optical computing.

Neglecting the diffraction limit of optical systems, Collins derived the following formula[16].

$$U_2(x_2,y_2)=\frac{\exp(ikL)}{i\lambda B}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}U_1(x_1,y_1)\exp\{\frac{ik}{2B}[A(x_1^2+y_1^2)+D(x_2^2+y_2^2)-2(x_1x_2+y_1y_2)]\}dx_1dy_1 \qquad (3)$$

Where L is path along the axis, U1(x1, y1) is light complex amplitude of the incident plane, and U2(x2, y2) is complex amplitude of the observation plane through the optical system.

III. ANALYSIS OF OPTICAL PERFORMANCE OF MOSC

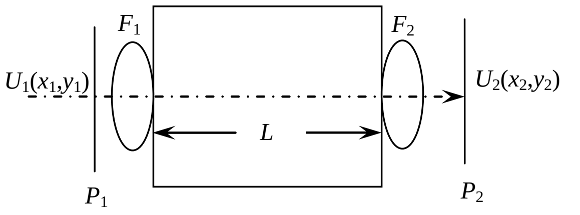


Figure 4. The schematic diagram of light propagation in MOSC

As shown in Fig.4, the problem of light transmitting in MOSC can be considered as light wave transmitted a certain distance L through the lens F1 focusing and injected through lens F2 focusing. Considering the light incident plane as a reference plane P1 and the light receiving planes as a reference plane P2, P1 and P2 constitute a paraxial imaging system, whose transformation matrix elements is given by the ABCD system. The relationship between the incident plane P1 wave field U1(x1, y1) and the receiving planes P2 wave field U2(x2, y2) satisfies the Collins formula (3). ABCD matrix is:

$$\begin{bmatrix}A & B\\ C & D\end{bmatrix}=\begin{bmatrix}1 & 0\\ -\frac{1}{f} & 1\end{bmatrix}\begin{bmatrix}1 & 0\\ 0 & \frac{n_2}{n_1}\end{bmatrix}\begin{bmatrix}1 & L\\ 0 & 1\end{bmatrix}\begin{bmatrix}1 & 0\\ 0 & \frac{n_1}{n_2}\end{bmatrix}\begin{bmatrix}1 & 0\\ -\frac{1}{f} & 1\end{bmatrix}$$
$$=\begin{bmatrix}1-\frac{n_1}{n_2}\frac{l}{f} & \frac{n_1}{n_2}l\\ -\frac{2}{f}+\frac{n_1}{n_2}\frac{l}{f^2} & -\frac{n_1}{n_2}\frac{l}{f}+1\end{bmatrix} \qquad (4)$$

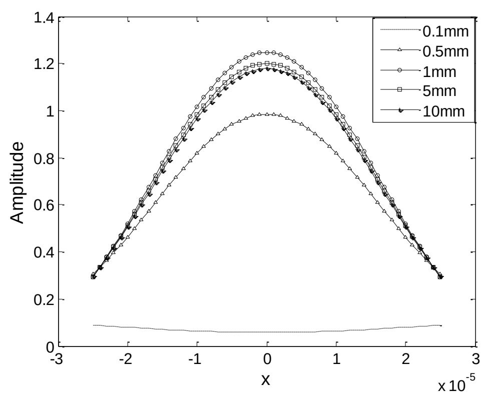
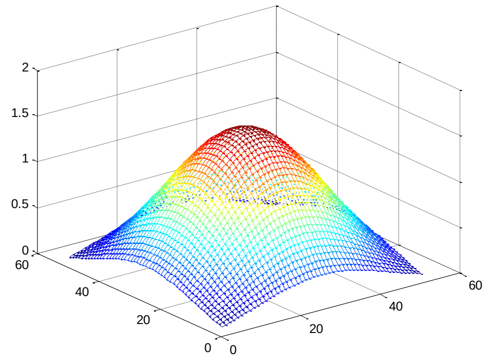
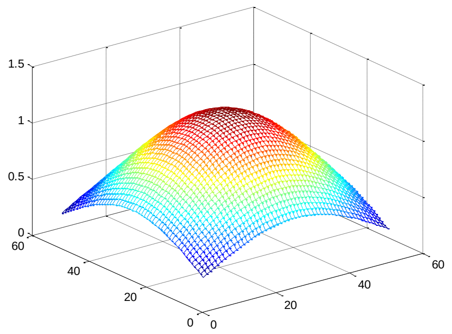


Figure 5. The relationship between the output light amplitude and the lens focal length

Assuming the light amplitude distribution of the incident plane is constant, the output light amplitude varies as a function of the lens focal length, which is calculated from ABCD matrix and Collins formula calculation.



(a)



(b)

Figure 6. 3D images of the output light focusing with the focal length of 1mm (a) and 0.8mm (b)

The relationship between the output light amplitude and the lens focal length is shown in Fig.5. Improper selection of focal length not only cannot focus light rays, but also disperse the energy. By means of calculation, when the lens focal length is 1mm, the best energy focus can be achieved and the 3D images of the output light focusing spot with two different focal lengths are shown in Fig. 6.

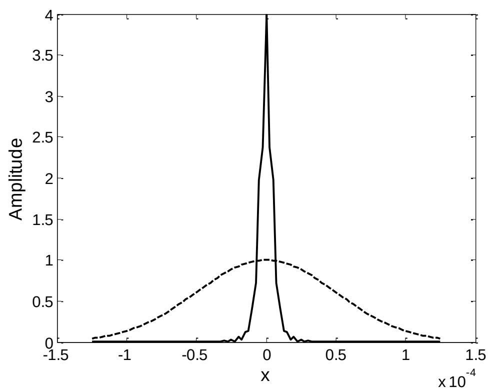


Figure 7. The comparison of the input (dotted line) and output (solid line) light amplitude

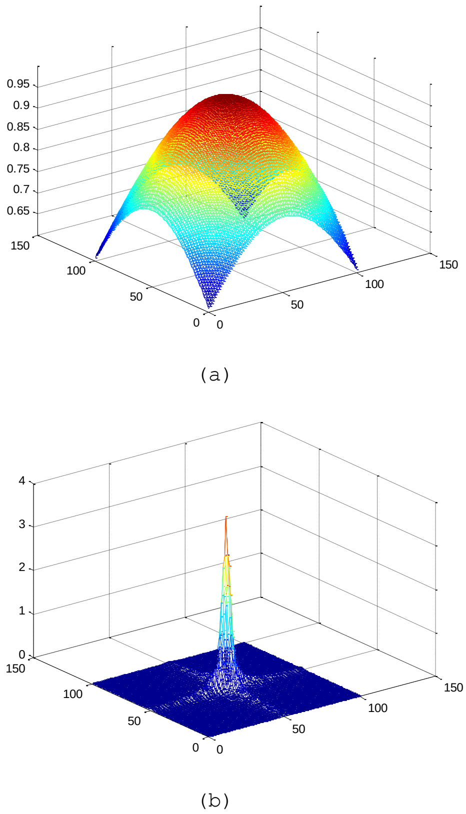


Figure 8. 3D images of the input (a) and output (b) light amplitude

Assuming the optical field distribution on the incident plane follows a Gauss distribution, the comparison of amplitude of the input (dotted line) and output (solid line) light through MOSC is shown in Fig.8. Obviously, energy of the light though MOSC is focused in a smaller range. The 3D images of the input and output light amplitude are shown in Fig.8.

The output light from the source is sent into the MOSC and focused by the lens F1 and F2. After propagating a distance z, the light enters the detector. The ABCD matrix is:

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix} = \begin{bmatrix} 1-\frac{n_1}{n_2}\frac{l}{f}-\frac{2z}{f}+\frac{n_1}{n_2}\frac{lz}{f^2} & \frac{n_1}{n_2}l-\frac{n_1}{n_2}\frac{lz}{f}+z \\ -\frac{2}{f}+\frac{n_1}{n_2}\frac{l}{f^2} & -\frac{n_1}{n_2}\frac{l}{f}+1 \end{bmatrix} \quad (5)$$

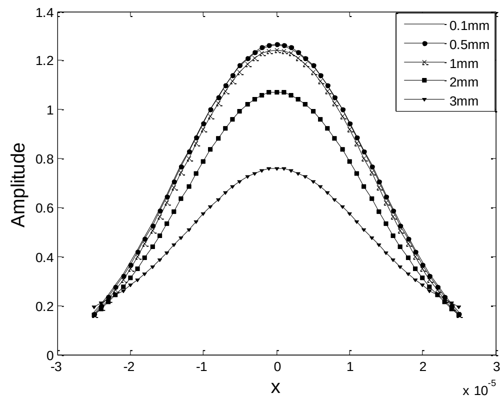


Figure 9. The relationship between the output light amplitude and distance z

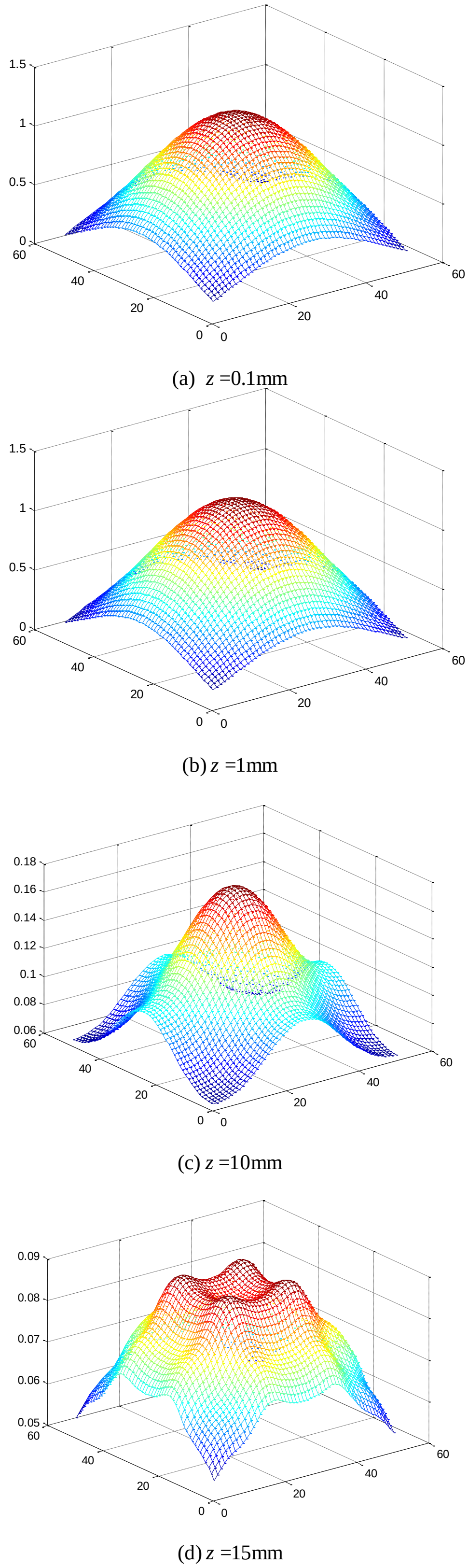


Figure 10. 3D images of the relationship between the output light amplitude and distance z

The light amplitude gathered in the detector changes with the distance z between the detector and lens F2. As shown in Figure 10, the relative intensity will decline as soon as the distance z is more than 1mm. So the detectors should be placed in a suitable location to get the best energy coupling. The relationship between the output light amplitude and distance z is shown in Fig.9 and the corresponding 3D images are shown in Fig.10.

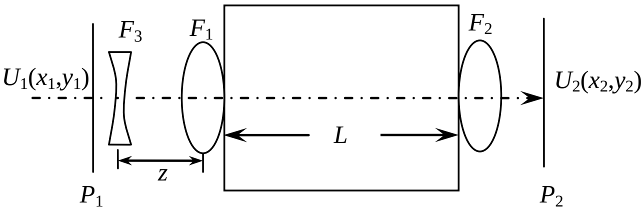


Figure 11. The schematic diagram of the optical wave field transmission through the turning coupling component

Fig.11 shows that, if the light emitted from the source is spherical wave, it can be regarded as a negative lens F placed near the light source, and the focal length of negative lens F is –d. The *ABCD* matrix is:

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix} = \begin{bmatrix} 1-\frac{n_1}{n_2}\frac{l}{f}+\frac{z}{d_0}-\frac{n_1}{n_2}\frac{lz}{fd_0}+\frac{n_1}{n_2}\frac{l}{d_0} & z-\frac{n_1}{n_2}\frac{lz}{f}+\frac{n_1}{n_2}l \\ -\frac{2}{f}+\frac{n_1}{n_2}\frac{l}{f^2}-\frac{2}{f}\frac{z}{d_0}+\frac{n_1}{n_2}\frac{lz}{f^2 d_0}-\frac{n_1}{n_2}\frac{f}{ld_0}+\frac{1}{d_0} & -\frac{2z}{f}+\frac{n_1}{n_2}\frac{lz}{f^2}-\frac{n_1}{n_2}\frac{l}{f}+1 \end{bmatrix}$$

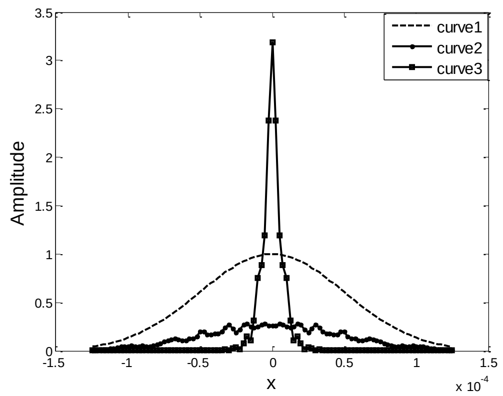


Figure 12. The comparison of the input and output light amplitude

When the optical beam emitted from the light source is expanded by a negative lens, the center beam intensity will decrease. But the energy can be focused again after propagating through MOSC, which is shown in Fig.12. Curve 1 is the input light amplitude distribution; curve 2 is the light amplitude distribution after negative lens; curve 3 is the light amplitude distribution after MOSC.

IV. CONCLUSIONS

In this paper, a method using Collins formula was put forward, aiming to analyze prism couple and waveguide propagation 90^0 turning coupling; meanwhile, the optical performance of MOSC based on this method was analyzed. The simulation results indicate that micro-component can reduce the coupling loss during the optical energy transmission effectively, and it is estimated that the coupling efficiency can be enhanced to 78% theoretically.

ACKNOWLEDGMENT

The author thanks the financial support of the National Natural Science Foundation of China, grant 61307038 and 11304396.

REFERENCES

[1] J.W Goodman, F. J Leonberger, S. -Y Kung, et al.. "Optical Interconnection for VLSI Systems," Proc. IEEE, Vol.72, 1984.07, pp.850~866

[2] J.A.Kash, F.E.Doany, L. Schares, et al. "Chip-to-chip optical interconnects," Proceedings of OSA/OFC, 2005, OFA3

[3] T.Mikawa, M.Kinoshita, K.Hiruma, et al. "Implementation of Active Interposer for High-Speed and Low-Cost Chip Level Optical Interconnects," IEEE Journal of Selected Topics in Quantum Electronics, Vol.9, 2003.02, pp. 452~459.

[4] Feng Xianghua, Wen Changli, Ji Jiarong, et al. "Studying of Polysiloxane Multimode Optical Ridge Waveguides Applying in Optical Interconnection," J. Optoelectronics·Laser, Vol.22, 2011.01, pp.38~41

[5] Sung Hwan Cho, "Optofluidic Waveguides in Teflon AF-Coated PDMS Microfluidic Channels," IEEE Photon. Technol. Lett., Vol.21, 2009.08, pp.1057~1059

[6] Feng Xianghua, Ji Jiarong, Dou Wenhua, "Study on the Bending Loss of Polysiloxane Optical Waveguides for Optical Interconnection," Acta Optica Sinca, Vol.32, 2012.08, pp.08230031~4

[7] Wang Xiaolong, Jiang Wei, Wang Li, "Fully Embedded Board-Level Optical Interconnects From Waveguide Fabrication to Device Integration ," Journal of Lightwave Technology, Vol.26, 2008.02, pp.243~250.

[8] A. Neyer, S. Kopetz, E. Rabe et al. "Electrical-Optical Circuit Board Using Polysiloxane Optical Waveguide Layer," Electronic Components and Technology Conference, Vol.55, 2005.03, pp.246~250.

[9] Alexei Glebov, San Mateo, et al. "Flexible Optical Waveguides for Backplane Optical Interconnections," US:0201707, 2005.

[10] Brian M. Davies, Ray T. Chen, Jian Liu, et al. "Holographic Optical Devices For Transmission of Optical Signals," US:6269203, 2001.

[11] Gary gunn. Silicon, "Photonics Poised to Invade Local Area Networks," Photonics Spectra, Vol.40, 2006.03, pp.62～68.

[12] X.feng, J.Ji, W.Dou, "Design and analysis of waveguide grating coupling with gradually changing periods for optical interconnection," .Proceedings of SPIE, 2010, pp.84823 1~12

[13] A.Yariv and M.Nakamura, "Periodic structure for integrated optics ," IEEE J.Quantum Electron., Vol.13, 1977.04, pp. 233~253

[14] Jeong Su Yang, Chul Hyun Choi, Beom-hoan O, et al. "Design and characterization of an out-of-plane polymer waveguide," Proceedings of SPIE, 2007, pp.6476:647611

[15] J .W. Goodman, "Fourier optical theory guide," Beijing: Science Press, 1976, pp.309~311

[16] Li Junchang, "Diffraction of laser and calculation on thermal acting ," Beijing: Science Press, 2002, pp.81～97