Design technique of crossed-gratings for beam couplers in large-core optical fibers

Hideyuki Tanaka, Takeshi Kobayashi, Tetsuya Saitoh, Yoshiyuki Suzuki,
and
Shigeru Kawai[*]
Fuji Electric Corporate Research and Development, Ltd., Yokosuka, 240-0194 Japan
Phone:+81-468-57-6732, Fax: +81-468-57-6946, E-mail:tanaka-hideyuki@fujielectric.co.jp
[*]Department of Electronics, University of Industrial Technology, Sagamihara, 229-1196 Japan
Phone:+81- 42-763-9199, Fax: +81-42-763-9199, E-mail: skawai@uitec.ac.jp

1. Introduction

Large-core optical fibers such as plastic optical fibers (POFs) are expected as short-range fiber optic communication systems because these optical fibers have large alignment tolerances. In fiber optic communication systems, coupling and branching functions are necessary. Coupling devices for single-mode optical fibers are commercially available, however it is not easy to find them for multi-mode optical fibers. Especially it is difficult to fabricate them for large-core optical fibers by using ordinary techniques. Diffractive optical elements (DOEs) designed by computers may achieve those devices [1-3]. One of the problems for the DOEs is their low diffraction efficiencies. In multi facet DOEs, it is easy to increase their diffraction efficiencies, however their facet period causes some noise beams and they decrease the redundancy for DOEs such as the allowance for the beam distribution dispersion of light sources. Dammann gratings[4] have been well known for high-efficiency multi-beam composers, however those diffraction patterns are limited for regular interconnections.

We propose a novel design technique for DOE with high diffraction efficiency, which is suitable for multi-fanout fiber optic communication systems. Our proposed crossed-grating is achieved by superimposing ordinary blazed gratings, i.e. single fanout DOEs, incoherently. In this paper, we describe the design technique, simulation results and experimental results of DOEs.

2. Design of The Grating

Optical couplers in fiber optic communication systems are generally required to divide a single input signal into several output signals. These optical couplers should be with low loss. In some cases such as for level monitoring, the branching ratio is not equal for all outputs. We consider the optical couplers with an unequal branching ratio. For these applications, the branching element should have functions of arbitrary diffraction directions and branching ratios.

Our proposed design technique includes superimposing ordinary single blazed gratings[5]. Figure 1 shows coordinate systems and denotations for the following descriptions. When a plane wave is vertically incident on a single blazed grating, the phase distribution for diffracted light waves on the gratings are shown by

$$\begin{aligned} b(x,\ y) &= \exp\left[2\pi a i (x\cos\phi + y\sin\phi)/p\right]\mathrm{rect}\left[(x\cos\phi + y\sin\phi)/p\right] \otimes \mathrm{comb}\left[(\cos\phi + y\sin\phi)/p\right] \\ &= \exp\left[i\mathbf{k}\cdot\mathbf{x}a\right]\mathrm{rect}\left[\mathbf{k}\cdot\mathbf{x}/2\pi\right] \otimes \mathrm{comb}\left[\mathbf{k}\cdot\mathbf{x}/2\pi\right], \end{aligned} \tag{1}$$

where rect[x]=1 ($|x| \geqq 1/2$), =0 ($|x| < 1/2$), comb[x] $\equiv \sum_{n=-\infty}^{\infty} \delta(x-n)$, and p and $\delta(x)$ are respectively the grating pitch and the delta function, and the symbol $\otimes$ denotes a convolution. The parameter $\mathbf{k}$ is a grating vector and $\mathbf{x}$=(x,y). In Eq. (1), a coefficient "a" represents the shrinkage for the phase modulation of gratings. We call the "a" as phase shrinkage coefficient. The intensity distribution I(u,v) for the diffracted waves in Fraunhofer diffraction region

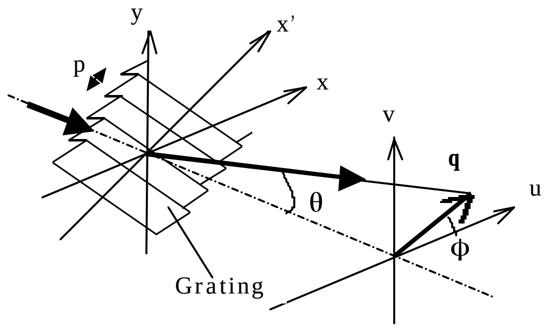

Fig. 1. Diffraction by a single blazed grating on xy-plane. Ray vector **q** of diffracted light is defined on uv-plane in Fraunhofer region. $p \sin\theta = \lambda$ where p is grating period and λ is wave length of incident light.

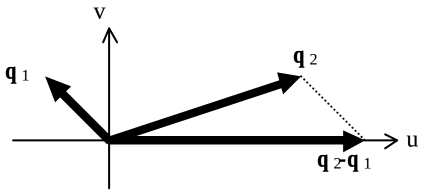

Fig. 2. Ray vectors $\mathbf{q}_1,\mathbf{q}_2$ of branched lights on uv-plane.

is given by the Fourier transform.

$$\begin{aligned} I(u,v) &= \left| FT\left[b(x,y)\right]\right|^2 \\ &= \left| p^2 \mathrm{sinc}\left[p(u\cos\phi + v\sin\phi) + a\right] \mathrm{comb}\left[p(u\cos\phi + v\sin\phi)\right]\delta(-u\sin\phi + v\cos\phi)\right|^2, \end{aligned} \qquad (2)$$

where FT[ ] means the Fourier transform and the function sinc[x] = $\sin(\pi x)/\pi x$. In Eq. (2), when the phase shrinkage coefficient a is equal to 1, which is equivalent to ordinary blazed gratings whose output intensity concentrates on the first order diffraction beams. In the case of $0 < a < 1$, other diffraction light beams appear. No diffraction occurs in the case of a = 0. In the proposed technique, we use both the 0th and the 1st order diffraction beams. The phase shrinkage coefficient satisfies the following equation for any branching ratios r.

$$r = r_1/r_0 = \mathrm{sinc}^2[a-1]/\mathrm{sinc}^2[a]$$

where r_0 and r_1 denote relative intensities for the 0th and the 1st order, respectively. As shown in Fig. 2, the branched light beams of $\mathbf{q}_1$ and $\mathbf{q}_2$ with arbitrary propagation directions can be generated from the grating shown by

$$\begin{aligned} b_2(x,y) = {} & \exp\left[i(\mathbf{k}_2 - \mathbf{k}_1)\bullet\mathbf{x}a\right]\mathrm{rect}\left[(\mathbf{k}_2 - \mathbf{k}_1)\bullet\mathbf{x}/2\pi\right]\otimes \mathrm{comb}\left[(\mathbf{k}_2 - \mathbf{k}_1)\bullet\mathbf{x}/2\pi\right] \\ & + \exp\left[i(\mathbf{k}_1\bullet\mathbf{x} + c)\right]\mathrm{rect}\left[\mathbf{k}_1\bullet\mathbf{x} + c/2\pi\right]\otimes \mathrm{comb}\left[\mathbf{k}_1\bullet\mathbf{x} + c/2\pi\right], \end{aligned} \qquad (3)$$

where $\mathbf{k}_k = (2\pi/\lambda)\mathbf{q}_k$ (k=1,2) and $\mathbf{q}_k = \sin\theta_k\,(\cos\phi_k, \sin\phi_k)$. The first term in the right hand side of Eq. (3) describes the 0th order and the 1st order diffraction beams of ($\mathbf{q}_2$-$\mathbf{q}_1$). The second term describes the deviation of $\mathbf{q}_1$. An arbitrary constant "c" denotes an initial phase value. As the result of the coincidence for these terms, the 0th order beam of the first term becomes $\mathbf{q}_1$ and the first order beam of the first term becomes $\mathbf{q}_2$. From Eq. (3), intensities for the branched light beams are given by

$$\begin{aligned} I_2(u,v) &= \left| FT\left[b_2(x,y)\right]\right|^2 \\ &= \left| p_1^2 \mathrm{sinc}\left[p_1/p_2\left\{(up_2 - \lambda\cos\phi_2)\cos\phi_1 + (vp_2 - \lambda\sin\phi_2)\sin\phi_1\right\} + a\right]\right. \\ &\quad \times \mathrm{comb}\left[p_1/p_2\left\{(up_2 - \lambda\cos\phi_2)\cos\phi_1 + (vp_2 - \lambda\sin\phi_2)\sin\phi_1\right\}\right] \\ &\quad \left.\times\delta\left[\left\{-(up_2 - \lambda\cos\phi_2)\sin\phi_1 + (vp_2 - \lambda\sin\phi_2)\cos\phi_1\right\}/p_2\right]\right|^2 \end{aligned} \qquad (4)$$

Surface relief DOEs with phase distributions given by Eq. (3) are derived from

$$h_2(x, y) = \lambda/2\pi(n-1)\,\mathrm{mod}\left[a\,\mathrm{mod}\left[(\mathbf{k}_2 - \mathbf{k}_1)\cdot\mathbf{x},\, 2\pi\right] + \mathrm{mod}\left[(\mathbf{k}_1\cdot\mathbf{x} + c),\, 2\pi\right],\, 2\pi\right], \tag{5}$$

where mod [s, t] is the remainder of s divided by t and n is refractive index of the substrate.

Figure 3 shows the diffraction efficiencies for two output-beams vs. the phase shrinkage coefficient. The diffraction efficiencies for two output-beams depend on this coefficient. By controlling the coefficient, desired output-beam power ratios are obtained. The total diffraction efficiency has the value of 81 % when the output-beam power ratio is equal.

We designed a two-fanout DOE with the phase distribution by using the above design technique. Figure 4 shows coordinate systems and denotations for the following descriptions. The design parameters are that diffraction angle of beam1 and beam2 are 0.64 degs. and 1.43 degs., respectively. The designed DOE consists of two original gratings.

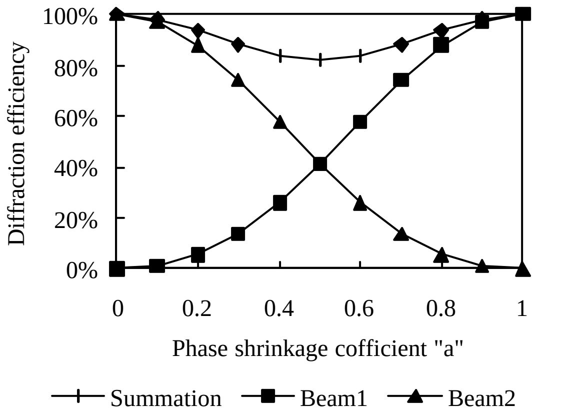

Fig. 3. Phase shrinkage coefficient “a” dependency of diffraction efficiencies.

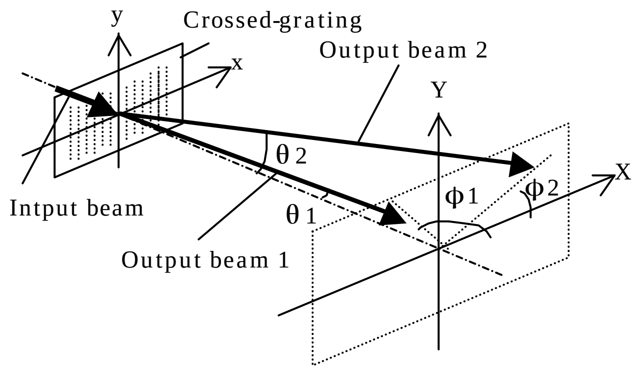

Fig. 4. Function of designed grating of two fanout.

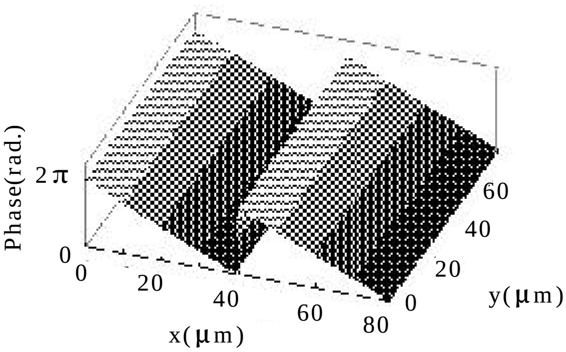

Fig. 5. Branching element.

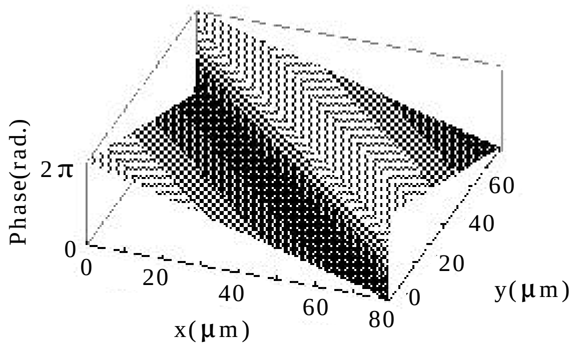

Fig. 6. Deviating element.

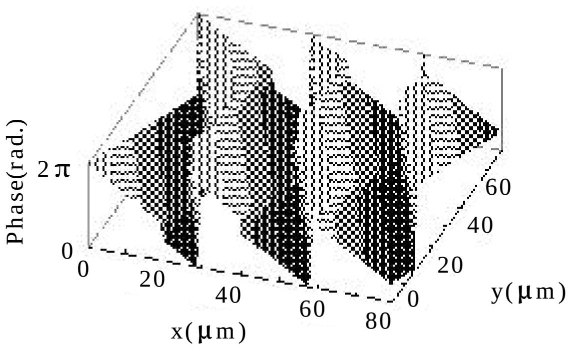

Fig. 7. Designed crossd-grating.

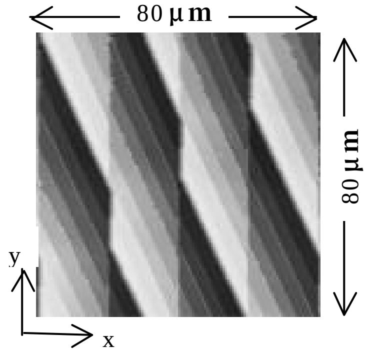

Fig. 8. AFM image of the fabricated DOE. Dark area is deep region.

The grating shown in Fig. 5 is a branching element for controlling the diffraction efficiencies, the power ratio of two output-beams and the angle between them. The grating shown in Fig.6 is a deviating element for shifting the direction of two output-beams at the same time without changing the diffraction efficiencies of two output-beams. The designed grating consists of above two gratings. The designed grating has the structure of crossed-gratings. Figure 7 shows the designed pattern. The phase distribution has periodic pattern for both to x and to y direction.

The calculated results for the designed 8 phase-levels DOE shows that total desired diffraction efficiencies and the power ratio for two output-beams are 88.3 % and 1:16, respectively.

3. Experiments and Discussions

We fabricated a two-fanout DOE with 8 phase-levels. The grating structure is fabricated by using ion-etching processes on a quartz substrate. The size of the unit cell caused by periodical structures is 80μm×80μm. The depth of the grating is 1.26μm, which is divided into 8 levels. Each step has the depth of 0.18μm. In order to form 8 phase-levels, three masks were used in fabrication processes. Figure 8 is an Atomic Force Microscope (AFM) image for the fabricated grating. It shows the front view of the unit cell whose size is well agreed with the designed value. The grating depth is also agreed with the designed value. In order to measure diffraction efficiencies for the fabricated grating, we used a He-Ne laser as an input light beam. The diffraction efficiency is defined as the diffracted light power divided by total transmitted light powers. The measured diffraction efficiency was 82.9 % which was almost agreed with the calculated value of 88.3 %. The measured output-beam power ratio was 1:14.6 which was almost agreed with the calculated value of 1:16. We consider these results show the usefulness for the proposed technique described in Sec. 2.

The error for measured diffraction efficiencies may be primarily caused by fabrication profile errors. Multiple reflections in a substrate glass also may cause measurement errors. The diffraction efficiency of the designed DOE in Sec. 2 is expected up to 93 % when it is an ideal blazed grating.

We described the case that plane waves were incident to DOEs. DOEs with focusing function into optical fibers are also accomplished by superimposing zoneplate phase-distributions with focusing functions

4. Conclusions

We proposed a novel design technique for multi-fanout DOEs with high diffraction efficiencies. This technique makes it possible to control both diffraction directions and output-beam power ratio. It easily provides phase distributions for DOEs without iterative calculation algorithms. The concept of this technique includes superimposing blazed gratings. This design technique provides DOEs with high diffraction efficiency of more than 81 % by computer simulations based on Fraunhofer diffractions. An output-beam power ratio from the DOEs can be easily changed by controlling phase shrinkage coefficients. We successfully fabricated a two fanout DOE with 1:16 output-beam power ratio designed by this technique. Experimental results of diffraction efficiencies are well agreed with the simulation result of 88 %. This technique may be suitable for designing large-core beam couplers with unequal output-beam power ratios.

References

1. S. Kawai and Y. Kohga , *Jpn. J. Appl. Phys.* **30**, pp. L2101-L2103, 1991.
2. J. R. Fineup, *Opt. Eng.* **19**, pp. 297-305, 1980.
3. M. R. Feldman and C. C. Guest, *Appl. Opt.* **14**, pp. 479-481, 1989.
4. D. Prongué, H. P. Herzig, R. Dändliker, and M. T. Gale *Appl. Opt.* **31**, pp. 5706-5711, 1992.
5. G.J. Swanson, *MIT Tech.Rep.* **854**, 1989.