Focusing and coupling properties of collective micro-optics on fiber ribbon

M Thual, J Lostec, D Pavy, M Gadonna, P. Chanclou

► To cite this version:

M Thual, J Lostec, D Pavy, M Gadonna, P. Chanclou. Focusing and coupling properties of collective micro-optics on fiber ribbon. Optical Engineering, 2000, 39 (2), pp.387. 10.1117/1.602375. hal-02920598

HAL Id: hal-02920598

<https://hal.science/hal-02920598>

Submitted on 24 Aug 2020

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

Focusing and coupling properties of collective micro-optics on fibre ribbon

P. Chanclou, M. Thual, J. Lostec, D. Pavy, and M. Gadonna.

FRANCE TELECOM, CNET, DTD/PIH
2, avenue Pierre Marzin, F22307 LANNION CEDEX FRANCE

Phone: 33 2 96 05 35 81

Fax: 33 2 96 05 20 65

e-mail: philippe.chanclou@cnet.francetelecom.fr

Abstract. A collective micro-optics is developed for coupling laser diode arrays to single mode-fibre ribbons. The arrangement consists of graded index multimode fibre ribbons and coreless silica fibre ribbons of calibrated lengths which are spliced and cleaved collectively. Coupling losses of 1.07 ± 0.11 dB with a working distance of 30.4 ± 1.2 μm are achieved. A theoretical model which predicts the coupling efficiency as a function of the lengths of the sections, is also established.

Subject terms: micro-optics; optical design; fibre optics; lasers; array; lenses; optoelectronic packaging.

1 Introduction

The large scale deployment of optical fibres in the access network will require the development of low cost, small package size and multichannel optical and optoelectronic modules [1,2,3]. Today, the packaging of the laser diodes remains one of the most critical steps. It is generally based on an active assembling which takes a long time: each laser is activated and individually positioned in front of each fibre.

To overcome this difficult problem, we investigate a new method which permits a passive assembling of a laser array with a single-mode fibre ribbon. Our approach relies on a very good matching of laser an fibre spot sizes, by using large spot size lasers and specially developed new micro-optics. Microlenses fitted at the ends of optical fibres were first introduced to improve coupling between laser diodes and single-mode optical fibres [4,5,6,7]. Our micro-optics is based on a fibre ribbon shape arrangement which is spliced at the end of the single-mode fibre ribbon. Low coupling loss, wide misalignment tolerances, long working distance, low return loss, and small package volume could be achieved. The fabrication process is easy and fairly compatible with mass production. The principle and first results have been previously published [8,9]. Here, we present a theoretical modelling of coupling loss properties of these micro-optics compared with experimental results.

2 Principle and Fabrication

As shown in Fig. 1, the micro-optics is made of standard ribbons including four 250 μm spaced fibres. It is composed of a graded-index 85/125/250 (GRIN) fibre section which acts as a GRIN lens which is maintained at the proper distance from the G652 single-mode fibre (SMF) by a coreless silica fibre section.

Fig. 1 Schematic representation of optical coupling arrangement between Laser Diode array and SMF ribbon.

Fig. 2 Photograph of the micro-optics ribbon.

The fabrication process [8,9] is collective as only ribbons of GRIN, silica and single-mode fibres are cleaved and spliced. Commercially available ribbon splicer and cleaver are used. An important advantage is that the fibre outer diameter of 125 μm remains unchanged along the length. Neither diameter bubble or conical end shape occurs during the process. This micro-optics is called GRADISSIMO in view of the different sections of GRADed Index, Silica and Single MOde fibres.

3 Focusing Properties

As shown in Fig. 3, the silica section allows to expand the optical beam from SMF, in order to use the largest useful area of the GRIN fibre. The interest of this solution is to provide a larger range of the spot size variation than in a configuration without silica [6] (Selfoc configuration). The mode expansion in the GRIN section is only limited by the core diameter. The length of the GRIN section is calculated to obtain the required spot size and working distance.

Fig. 4 shows the spot size diameter (defined at $1/e^2$ of the maximum of intensity) at the focal point for varying lengths of GRIN and silica sections at 1.3 μm . The theoretical curves are in good agreement with measurements.

Fig. 3 Schematic illustration of the interest of silica section.

— with silica section
 without silica section

Fig. 4 Mode diameter at the focal point of the micro-optics ($L_s=0 \mu\text{m}$ (box) and $400\mu\text{m}$ (star)).

4. Coupling Loss Theory

The calculation of the coupling losses requires the study of the propagation in the various sections which compose the micro-optics. The scheme of the GRADISSIMO micro-optics is represented in Fig. 5. The coupling between the laser and SMF is improved by the GRIN lens [10]. The silica section length corresponds to the rear working distance of the GRIN lens.

Fig. 5 Structure of a lens system, which couples the radiation field of a source in an SMF.

The parameters used are denoted as ω_x and ω_y , the spot size radius at $1/e^2$ of the maximum of intensity for the laser diode (LD) field endface in the x and y directions, respectively. To simplify equations, it is assumed that $\omega_x=\omega_y=\omega$. ω_f is the spot size of the fundamental-mode LP01 field (approximated by a Gaussian field) of the SMF. L_w is the working distance in air between LD and micro-optics. L_g and L_s are the length of silica and GRIN sections. The Gaussian field distribution in the z propagation direction (one measures z from the waist) is given by

$$E(r, z) = \sqrt{\frac{2}{\pi}} \frac{1}{\omega(z)} \exp\left(-r^2\left(\frac{1}{\omega(z)^2} + \frac{jkn}{2R(z)}\right)\right) \quad (1)$$

where $k=2\pi/\lambda$ is the propagation constant in the index medium n and r measures the distance from the axis. $\omega(z)$ and $R(z)$ are determined using the spot size ω_0 at the beam waist as

$$\omega(z) = \omega_0 \sqrt{1 + \left(\frac{z}{z_0}\right)^2} \quad \text{and} \quad R(z) = \frac{z^2 + z_0^2}{z}. \quad (2)$$

The parameter $z_0=k\omega_0^2/2$ is the confocal (Fresnel) distance of the beam. We have similar equations for the SMF beam in the silica where the refractive index is n_s . The length of the silica section is limited by

the beam expansion from the SMF. Because of the limited useful diameter of the GRIN fibre ($\omega(L_s) < \phi_g$) the maximum length of the silica section is $L_{lim}=680 \mu\text{m}$ at $1.3\mu\text{m}$. The GRIN section is a medium where the refractive index varies quadratically with the distance r from the optical axis. This multimode fibre has a $85 \mu\text{m}$ core diameter, the refractive index along the optical axis equal to 1.472 and a quadratic gradient constant g equal to 4.326 mm^{-1} at $1.3 \mu\text{m}$.

$$n(r) = n_0 \left(1 - \frac{g^2}{2} r^2 \right) = n_0 \left(1 - \frac{n_2}{2} r^2 \right) \quad \text{for } 0 \leq r \leq \phi_g \quad (3)$$

$$= n_{cl} \quad \text{for } \phi_g < r \leq \phi_f$$

The propagation laws for Gaussian beams in such medium, are described by H. Kogelnik [11,12]. The spot size $\omega_g(z)$ and radius of curvature $R_g(z)$ in the z direction are given by

$$\omega_g(z) = \sqrt{\frac{2}{-\text{Im}[Q(z)]}} \quad \text{and} \quad R_g(z) = \frac{k_0}{\text{Re}[Q(z)]}, \quad (4)$$

where $k_0=2\pi n_0/\lambda$ and $k_2=2\pi n_2/\lambda$. Parameter Q is defined as

$$Q = Q_m \frac{Q_1 + Q_m + (Q_1 - Q_m)e^{2j\gamma z}}{Q_1 + Q_m - (Q_1 - Q_m)e^{2j\gamma z}}, \quad (5)$$

with

$$Q_m = -j\sqrt{k_0 k_2} \quad \text{and} \quad \gamma = \sqrt{\frac{k_2}{k_0}}, \quad (6)$$

where Q_1 is the beam parameter at the input plane in the graded index medium at $z=0$. As sketched in Fig. 6, the beam expansion of the gaussian field from LD in the graded index medium is larger than the core diameter of the GRIN fibre. The Gaussian field distribution is then truncated by the cladding during its propagation in the Selfoc [13].

Fig. 6 Schematic illustration of beam truncation during propagation through the micro-optics.

Fig. 7 Intensity distribution of SMF emission and LD emission in the integration plane.

The Gaussian field distribution on the wave plane section in the GRIN fibre, is truncated by the cladding. We equate the field distribution in this wave plane section as

$$E(r, z = L_w + L_\infty) = \sqrt{\frac{2}{\pi}} \frac{1}{\omega_g(L_w + L_\infty)} \exp\left(\frac{-r^2}{\omega_g(L_w + L_\infty)^2}\right) \quad \text{for } 0 < r \leq \phi_g \quad (7)$$

$$= 0 \quad \text{for } r > \phi_g$$

The truncation coefficient of the Gaussian field is defined as

$$\tau = \phi_g / \omega_g(L_w + L_\infty). \quad (8)$$

The lengths of the silica and GRIN sections are defined to optimise the coupling efficiency between the LD array and SMF ribbon. Note that the model takes into account the fact that the beam propagation is truncated by the optical cladding of the GRIN sections. The optimum lengths of silica and GRIN sections for the LD coupling is a compromise between the equality of mode diameters and the truncation of the beam. The optical-power coupling efficiency between the mode of the SMF and the beam of semiconductor laser, in the integration plane is evaluated

$$\eta = \frac{P_{\text{coupled in SMF}}}{P_{\text{emitted LD}}} = \left| \int_0^{+\infty} \int_0^{2\pi} E_i E_f^* r dr d\theta \right|^2 \quad (9)$$

where r and θ are polar co-ordinates. The field distribution is adequately approximated by a Gaussian mode. This Gaussian distribution along the optical axis after the interface between the selfoc and silica section, can be expressed for SMF emission through the silica section by

$$E_f(r, z = L_s) = \sqrt{\frac{2}{\pi}} \frac{1}{\omega_f(L_s)} \exp\left(-r^2 \left(\frac{1}{\omega_f(L_s)^2} + \frac{jk_o}{2R_f(L_s)} \right)\right), \quad (10)$$

where n_s is equal to the refractive index of the silica and for LD emission through GRIN section by

$$E_i(r, z = L_w + L_g) = \sqrt{\frac{2}{\pi}} \frac{1}{\omega_g(L_w + L_g)} \exp\left(-r^2 \left(\frac{1}{\omega_g(L_w + L_g)^2} + \frac{jk_o}{2R_g(L_w + L_g)} \right)\right) \quad \text{for } 0 < r \leq R_T \quad (11)$$

$$= 0 \quad \text{for } r > R_T$$

where R_T is the truncation radius of the beam in the integration plane. We consider that the truncation coefficient in the integration plane or the wave plane section is similar. By using Equ. (8), the truncation radius is given by $R_T = \tau \times \omega(L_w + L_g)$. (12)

Inserting the field distributions (10,11) into the formula (9) of the coupling efficiency yields

$$\eta = \frac{4}{\left(\omega_f(L_s) \times \omega_g(L_w + L_g)\right)^2} \left| \frac{1 - \exp(-\beta R_T^2)}{\beta} \right|^2, \quad (13)$$

where has been defined the parameter

$$\beta = \frac{1}{\omega_f^2(L_s)} + \frac{1}{\omega_g^2(L_w + L_g)} + i \frac{k_o}{2} \left(\frac{1}{R_f(L_s)} + \frac{1}{R_g(L_w + L_g)} \right). \quad (14)$$

The surface reflection and wavefront distortions of the micro-optics are ignored in the coupling efficiency formula. The wavefront distortions are caused by insufficient polishing or other surface deficiencies [14]. The roughness parameters of the cleaved surface is measured using a differential interference pattern. Since no polishing was applied at the end-face of the ribbon, the measurements was $\sigma = 30$ nm. The stochastic wavefront distortions cause a reduction of the coupling efficiency by a factor $\exp(-(k\sigma)^2)$.

The reduction of the coupling efficiency is about -0.2 dB. Calculated coupling losses in this micro-optics are used to understand the influence of parameters involved in the design of the micro-optics.

5 Coupling Properties

The micro-optics ribbon is held in a silicon fibre-carrier fitted with four 250 μm spaced V-grooves. For these experiments a tapered LD at 1.3 μm (Alcatel) was used whose emitting half angles (and radius mode) defined by the far-field at $1/e^2$ of the maximum of intensity, are 10.3° ($\omega = 2.3 \mu\text{m}$) and 10.5° ($\omega = 2.23 \mu\text{m}$) in the parallel (x) and perpendicular (y) directions. Fig. 8 shows the lensed ribbon coupled with the LD array.

Fig. 8 Photograph of a four-channel LD array chip coupled with a micro-optics ribbon

Tapered LD	coupling loss	working distance
fibre 1	-0.96 dB	29.2 μm
fibre 2	-1.04 dB	31.4 μm
fibre 3	-1.11 dB	31.6 μm
fibre 4	-1.18 dB	31.0 μm

Fig. 9 Optical coupling efficiency of each fibre of the ribbon measured at the optimum position in front of a single LD.

In order to evaluate the homogeneity of the micro-optics (Fig. 9), the coupling efficiency of each fibre of the ribbon is measured at the optimum position in front of a single LD. The achieved coupling efficiency, defined as $10\log(P_{\text{coupled}}/P_{\text{emitted LD}})$, is -1.07 ± 0.11 dB for the LD with a working distance of $30.4 \pm 1.2 \mu\text{m}$. The lengths of silica and GRIN are optimised for a working distance of 30 μm . The lengths can also be optimised for other working distances (Fig. 10). As shown in Fig. 11, the efficiency of optimised micro-optics depends on the working distance.

Fig. 10 Length of GRIN and silica sections for optimal micro-optics at different working distances.

Fig. 11 Coupling loss characteristics of optimal micro-optics at different working distances.

Experimental results are reported to show the good flexibility on section lengths, to obtain the desired working distance L_w . The coupling loss increases, due to the aperture limitation and truncation of the Gaussian field as a function of the working distance. Nevertheless this flexibility of the working distance allows the decrease of the optical feedback in LD resulting from the proximity of the SMF.

The measurements of coupling losses as a function of axial and lateral displacements, are shown in Fig. 12 for micro-optics optimised at a working distance of 75 μm . The optical coupling of the micro-optics is compared with a butt coupling of cleaved SMF. Fig. 12(a) shows coupling loss

characteristics as a function of the working distance for measured values, according to theory. Fig. 12(b) shows measured coupling loss characteristics as a function of the lateral displacement in the x and y directions. The light emission of the LD is almost circular, the loss increments in x and y displacements are not much different.

Fig. 12 Coupling-loss characteristics as a function of axial displacement (a) and lateral displacement (b) of a micro-optics optimised at a working distance of 75 μm . The dashed lines are theoretical curves.

The optical alignment tolerance is $\pm 16 \mu\text{m}$ in the axial direction with 1 dB excess loss. It is better than SMF in the $+40 \mu\text{m}$ to $-85 \mu\text{m}$ range around the optimum coupling position. The lateral tolerance is $\pm 1.8 \mu\text{m}$ with 1 dB excess loss that is better than SMF in the $\pm 2.4 \mu\text{m}$ range. The fluctuation of the coupling-loss due to optical feedback of LD to the fibre, decreases when micro-optics is used. The oscillation amplitude of the coupling loss along the z axis is about $\pm 0.3 \text{ dB}$ for cleaved SMF and $\pm 0.1 \text{ dB}$ for GRADISSIMO due to the rather long working distance (75 μm).

Optical misalignment induce excessive coupling losses, but the manufacturing faults in silica and GRIN section lengths is also a source of excess loss. As shown in Fig. 13, the length tolerances of the GRIN and silica sections are $\pm 20 \mu\text{m}$ and $\pm 80 \mu\text{m}$ respectively, with 1 dB excess coupling loss between LD and the micro-optics. The length tolerances are much larger than the cleaving precision of $\pm 2 \mu\text{m}$, which provides a very tolerant fabrication process.

Fig. 13 Manufacturing tolerance of silica and GRIN section lengths.

The above-described micro-optics is coupled at LDs and optical sources with various field patterns, emitting at a wavelength of 1.3 μm . The silica and GRIN lengths are optimised for each radius

mode of optical source as shown in Fig. 14. Fig. 15 depicts the coupling efficiency against LD radius mode at a working distance $L_w=50\mu\text{m}$. The experimental results are in good agreement with the theoretical curve. The total coupling loss due to surface reflections and stochastic wavefront distortions is estimated to be -0.55 dB , which is taken into account in our calculation.

Fig. 14 Length of GRIN and silica sections for optimal micro-optics as a function of light source radius mode. The continuous lines are theoretical curves.

Fig. 15 Coupling loss characteristics as a function of light source radius mode at $L_w=50\mu\text{m}$. The continuous lines are theoretical curves.

6. Conclusion

To our knowledge GRADISSIMO is the first micro-optics designed and realised on a single-mode fibre ribbon arrangement. The feasibility of long working distances, high coupling efficiency and large positioning tolerances has been demonstrated. Moreover, the fabrication process is simple, collective, reproducible and therefore suitable with mass-production of multichannel optoelectronic modules. Finally, the modularity provided by the concept of GRIN and silica sections would allow to serve a wide variety of devices in the field of optical interconnection applications.

References

1. W. Unziker, "Low-cost packaging of semiconductor laser arrays", *Circuits&Devices* **13**, 19-25 (1997).
2. G. Nakagawa, "Highly Efficient Coupling Between LD Array and Optical Fiber Array Using Si Microlens Array", *Photonics Technology Letters* **5**, 1056-1058 (1993).
3. K. Shiraishi, "A fiber with a long working distance for integrated coupling between laser diodes and single-mode fibers", *Journal of Lightwave Technology* **13**, 1736-1744 (1995).
4. L. G. Cohen and M. V. Schneider, "Microlenses for Coupling Junction Lasers to Optical Fibers", *Appl. Opt.* **13**, 89-94 (1974).
5. K. Mathyssek, R. Keil, and E. Klement, "New coupling arrangement between laser diode and single mode fiber with high coupling efficiency and particularly low feedback effect", *ECOC'84*, paper 10A5, 1984.
6. R. Meilleur et al., "High power $1.48\mu\text{m}$ laser pump module using efficient and low feedback microlenses", *EFOC&N'93*, paper 119, pp. 205-209, July 1993.

7. K. Shiraishi et al., "A lensed-fiber coupling scheme utilizing a graded-index fiber and a hemispherically ended coreless fiber tip", *Journal of Lightwave Technology*, vol. 15, N°2, pp. 356-363, february 1997.
8. P. Chancelou, M. Thual et al., "Highly efficient collective coupling between laser diode and lensed fibre ribbon", in *Micro-optics Integration and Assemblies*, Proceedings of SPIE Vol. **3289**, pp97-102.
9. M. Thual, J. Lostec, P. Auvray, B. Clavel, French patent N° 96 10327, August 1996
10. William L. Emkey, Curtis A. Jack, "Analysis and evaluation of graded-index fiber-lenses", *Journal of Lightwave Technology* **5**, 1156-1164 (1987).
11. H. Kogelnick, "On the propagation of gaussian beams of light through lenslike media including those with a loss or gain variation", *Appl. Opt.* **4**, 1562-1569 (1965).
12. H. Kogelnick, "Laser Beams and Resonators", *Proc. IEEE* **54**, 1312-1329 (1966).
13. Y. Li and E. Wolf, "Focal Shift in Focused Truncated Gaussian Beams", *Opt. Comm.* **42**, 151-156 (1982).
14. B. Hillerich, "Influence of lens imperfections with LD and LED to single-mode fiber coupling", *Journal of Lightwave Technology* **7**, 77-86 (1989).