Arrayed Multimode Fiber to VCSEL Coupling for Short Reach Communications Using Hybrid Polymer-Fiber Lens

J. K. Kim, D. U. Kim, B. H. Lee, and K. Oh

***Abstract*—We report the novel method that can give high coupling efficiency between a vertical-cavity surface-emitting laser (VCSEL) array and a multimode optical fiber ribbon by using a hybrid-polymer-fiber lens technique. The coupling efficiency as high as 91% was achieved by optimizing the polymer lens curvature for the single source to the single fiber case. The longitudinal and the transverse coupling tolerances were enhanced with the introduction of a coreless silica fiber (CSF) segment between the fiber and the lens tip. The tradeoff between the high coupling efficiency and the large tolerance was experimentally observed. The technique was further applied to the coupling between a four-channel VCSEL array and a four-core fiber ribbon for short reach applications. The procedure of fabrication and the analysis of their optical characteristics are reported.**

***Index Terms*—Coreless silica fiber (CSF), coupling, lensed fiber, polymer, vertical-cavity surface-emitting laser (VCSEL) array.**

I. Introduction

With wide deployment of passive optical network and parallel optics applications including very short reach (VSR) communication systems, high efficiency, and low loss in the light source to optical fiber, especially fiber ribbon, coupling is becoming even more indispensable. Especially for VSR communication systems in the 850-nm spectral range, vertical-cavity surface-emitting lasers (VCSELs) and VCSEL array can play a major role in practical applications due to low threshold currents and high wall plug efficiencies [1], [2]. Compared with simple butt coupling, the need for a lens or microlens over the fiber end to enhance the coupling efficiency [3]–[5] is well-justified, but these methods require delicate alignment procedure along with a complicated packaging process. Although commercial VCSELs are routinely packaged with bulk microlenses, the demand for further integration is emerging such as in terms of the system form factor and packaging cost. High-coupling efficiency into optical fibers without additional bulk-optics would be one of the key features for optical component assembly in the immediate future.

To date, despite several methods having been reported for interconnecting optical ends without using bulky optics, they have some limits in their optical characteristics and fabrication processes [6]–[11]. The previously reported polishing and arc-discharge techniques to form the fiber lens required sophisticated mechanical processes and the flexibility to adjust the curvature radius of the fiber lens has been rather restricted [6]–[8]. The method using a graded index fiber could substitute the microlens but it was relatively accompanied with a high-cost system [7]–[9]. The tapered and chemical etching process caused high coupling loss due to a small curvature radius although it composed an arrayed system [10], [11].

The authors have reported a new hybrid-polymer-fiber lens consisting of a three-segmented structure: a conventional optical fiber, a coreless silica fiber (CSF), and a polymer lens tip. It showed very flexible control over the spot size and the working distance [12], [13]. Further, the proposed methods could realize a cost-effective system and the easy fabrication process enabled mass production. In this letter, we report two types of experimental implementations of 1) efficient VCSEL-to-graded index multimode fibers (GIMMFs), one-to-one coupling, and 2) VCSEL array-to-GIMMF ribbon, four-to-four coupling, which utilize the reported hybrid-polymer-fiber-lens technique with some modifications. The coupling between VCSELs and a GIMMF ribbon forms the backbone of VSR and parallel optics. The detailed procedure, analysis, and comparison are provided.

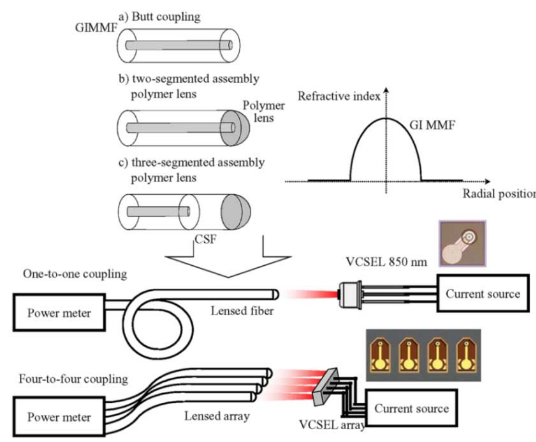

Fig. 1. Schematic diagram of the measurement setup. The photograph is top-view of the single VCSEL and four-channel VCSEL array chip. Here GIMMF and CSF are gradient index MMF and CSF, respectively.

II. Experiments and Results

The schematic diagram of the measurement setup is illustrated in Fig. 1. Three types of coupling schemes, from a source to a fiber, were tested: (a) butt-coupling, (b) coupling with a

Manuscript received January 19, 2007; revised April 6, 2007.

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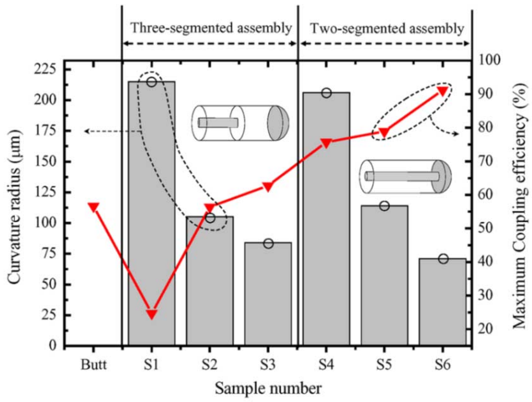
Digital Object Identifier 10.1109/LPT.2007.898790



Sample number	Butt	#1	#2	#3	#4	#5	#6
R (μm)	Inf	215	105	84	206	114	71
Lc(μm)	0	400	200	200	0	0	0
Maximum Coupling efficiency (%)	56.6	24.7	56.4	62.7	75.7	78.9	91.2

Fig. 2. Coupling efficiency for lensed fiber samples with various curvature radii and CSF length for the single VCSEL to GIMMF coupling.

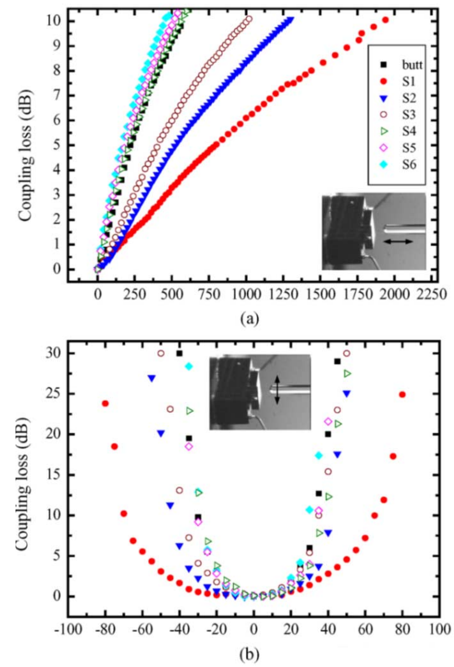


Fig. 3. Measured coupling loss as a function of (a) longitudinal and (b) transverse displacement for the GI MMF coupling.

two-segmented assembly polymer lens, and (c) coupling with a three-segmented fiber assembly. Note that in Fig. 1, case (c), the CSF (coreless single-mode fiber) was spliced to a GIMMF to control the beam spot size further. The optical power couplings in two different schemes were measured: 1) one fiber to one VCSEL coupling, and 2) one ribbon having four fibers to four VCSELs array coupling, as shown in the bottom of Fig. 1.

The VCSEL used in the experiments was operated in the spectral range centered at 850 nm. At room temperature, the typical output power was 2.0 mW with a driving current of 5 mA. The beam divergence was in the range of 14° to 30°, and the laser diameter was 18 μm at the active spot. The polymer lenses were formed with precise controlling of the viscosity and volume of the liquid polymer on a fiber tip, as reported by the authors [12], [13]. To prevent Fresnel reflection between the polymer lens and fiber, the refractive index of the polymer is adjusted to match that of fused silica. The polymer mainly consists of fluorinated oligomer and monomers with a 1 : 1 ratio along with the acrylate monomer of 3%–5% and a small dose of photoinitiator of 2%–4% for UV-curing. The GIMMF was a commercial one having a 50-μm graded index core and a 500-MHz $\cdot$ km bandwidth at 850 nm. The four-core fiber ribbon had the core-to-core distance of 250 μm, which matched with the chip-to-chip distance of the VCSEL array.

For the one-to-one coupling, seven samples were prepared: one for the butt-coupling, three for the two-segmented type, and three for the three-segmented one. The coupling efficiencies and the fiber lens parameters were measured and summarized in Fig. 2. In the butt-coupling case, a cleaved fiber end was directly butt-coupled to a VCSEL. The samples S1, S2, and S3 were in the same three-segmented fiber assembly type but had various values of polymer lens radii of curvature and CSF lengths. The samples S4, S5, and S6 were in the two-segmented fiber assembly, which had only the polymer lens without the CSF segment.

The experiments clearly showed that the coupling efficiency did depend on the curvature radius as well as on the length of the CSF. For a smaller radius of curvature, since the polymer lens focused the light tightly into the GIMMF core, it could result in a higher coupling efficiency. As far as the maximum coupling efficiency is concerned, the two-segmented fiber assembly case was better than the three-segmented one. The sample S6 showed the maximum coupling efficiency of as high as 91%. It means that, interestingly, the expansion of the beam diameter along the CSF region, which was very effective in the single-mode-fiber cases [12], [13], did not earn any benefits in the coupling with the GIMMF having a large core diameter.

The coupling loss induced by the longitudinal and the transverse displacements were, then, measured and summarized in Figs. 3(a) and (b), respectively. In contrast to the maximum coupling efficiency case, the tolerance to fiber-VCSEL displacement was improved in the three-segmented assembly, allowing longer working distances with stable alignment than the two-segmented assembly. It is noted that smaller polymer lens curvature and shorter CSF length resulted in worse tolerances against the longitudinal and transverse displacements. The two-segmented samples, S4, S5, and S6 without CSF, had almost the same tendency as the butt coupling case; they had higher coupling efficiencies but the tolerances were highly limited against displacements. The three-segmented samples, S1, S2, and S3, however, did show good coupling loss tolerance due to beam expansion along the CSF segments. Sample S1, which had the longest CSF length of 400 μm and the largest radius of curvature of 215 μm, resulted in the longest 3-dB coupling loss tolerances of 470 and ± 20 μm for the longitudinal and the transverse displacements, respectively. Comparing the experimental results in Figs. 2 and 3, it is confirmed that a tradeoff exists between the maximum coupling efficiency and displacement tolerance, so that optimization of the radius of

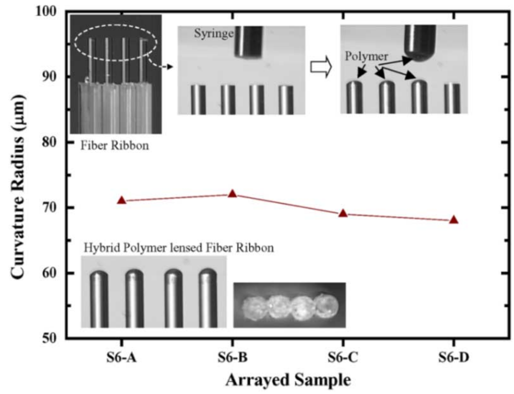


Fig. 4. Curvature radius uniformity of the lensed fiber ribbon. Photographs are the real images of the four-channel-ribbon fiber and its fabrication process.

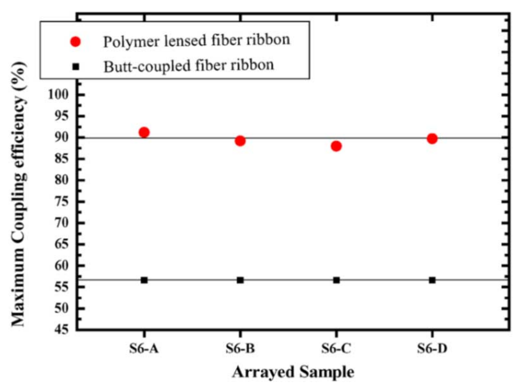


Fig. 5. Coupling efficiency uniformity of the lensed fiber ribbon versus butted fiber-ribbon.

curvature and the CSF length should be made for appropriate packaging of VCSEL with GIMMF pigtailed. The conventional lensed fiber has the maximum coupling efficiency of around 85%–90% in the case of the optimized source to multimode fiber (MMF), which is similar to the reported values in this study. However, detailed parametric studies have been very scarce, and it is noteworthy to experimentally investigate the tradeoff between coupling efficiency and displacement tolerance due to the existence of the CSF region.

We, then, further applied the hybrid polymer lens technique to the four-channel-VCSEL array to the four-channel-GIMMF-ribbon coupling. The four-channel ribbon fiber consisted of GIMMFs having 50-μm core was provided by Luvantix and the pitch between the cores was 250 μm, which matches the pitch of the four-channel VCSEL array. The VCSEL array from Optowell had the same specification as the single VCSEL. One of the key distinctive merits of the hybrid polymer lens technique [12], [13] is the capability to efficiently form multiple lenses over a fiber array with high uniformity. In the photographs of Fig. 4, the procedure of forming polymer lenses over the four-channel-GIMMF-ribbon is illustrated. The lenses had the similar specification with Sample S6 in Fig. 2. The data points in Fig. 4 show that the distribution of the curvature radius among the lensed fibers in the array was highly uniform. The variation of the curvature radii was less than 2.2%, with an average of 70 μm and a standard deviation of 1.58. The coupling efficiency between the four-channel VCSEL and the lensed fiber ribbon was measured and compared with the butt-coupling case in Fig. 5. The lensed fiber ribbon did show significant enhancement in the coupling efficiencies similar to the single-fiber lens case. The mean value of the coupling efficiency was 89.6% with a standard deviation of 1.02. The variation was below 1.14%, which manifests a strong potential in the parallel optic data communication applications.

III. Conclusion

Using novel hybrid polymer-fiber lenses, we have experimentally analyzed the coupling characteristics between a single VCSEL and a GIMMF, and a four-channel VCSEL array and a four-channel fiber ribbon. By varying the curvature radius of the polymer lens and the length of CSF, the coupling efficiency and loss could be optimized. The two-segmented polymer lens showed the maximum coupling efficiency over 91%, while the three-segmented polymer lens showed the 3-dB coupling loss tolerance of 470 and $\pm$50 μm for the longitudinal and the transverse displacements, respectively. We also confirmed that the proposed method could be directly applied to the coupling between a four-channel VCSEL array and a fiber ribbon. The coupling efficiency of over 89% and excellent channel-to-channel uniformity of 1.14% variation were successfully implemented, which could be directly applicable to VSR networks and parallel optics.

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