Abstract—In this paper, we report cost-effective light coupling methods for polymer optical fiber (POF) communication. Here, we compare the various optical coupling schemes in detail. By optical simulations, we analyze the conventional light coupling schemes, namely the direct coupling, lens coupling, and lensed fiber coupling. The simulation studies reveal that a lensed fiber tip particularly at the receiver side improves the light coupling efficiency to a great extent. The optimized lensed POF design confers an 85% coupling efficiency. Lensed POFs are realized with two low-cost fabrication methods. The characterization of the lensed POF are carried out to evaluate the lensing properties and hence to optimize the fabrication process.

Index Terms—Characterization, detector, fabrication, lensed fiber, optical coupling, polymer optical fiber, simulation.

I. INTRODUCTION

In the recent past, polymer optical fibers POFs found exciting applications as a low-cost alternative in home network, automotive, and short reach applications [1], [2]. The lower connection costs and other low cost factors made large-core multimode POFs attractive over single-mode fibers for short-distance communications [4]. POFs are large-core multimode optical fibers with very high numerical apertures. They have the advantages of optical fibers while maintaining the flexibility of copper cables in installation [3]. The major challenges for POF networks are low-cost components, their packaging, and the interfacing with the existing networks [5]. At present, both light emitting diodes (LEDs) and vertical cavity surface emitting lasers (VCSEL) are being used as the light source. They give the cost advantage over laser diode as the light source. Availability of high speed, high-performance VCSELs, and resonant cavity LEDs (RCLED) at a reasonable cost keep POF networks attractive for gigabit applications. Since POFs have a large core diameter, the coupling with the transmitter does not raise any serious light coupling issues. However, the large core diameters always results in severe power coupling losses at the receiver side. This in turn reduces the maximum communication link distance achievable. Realization of additional coupling elements brings in process complexities at an added cost. All these factors necessitate a cost-effective coupling method along with ease of installation, fiber plug-in modules, to keep POFs attractive in the market [6].

II. COUPLING METHODS

The conventional connector-less transceiver packages for POF communication use an aspherical lens or ball lens as an additional coupling element between the light source and POF or POF and detector [7]. The drawbacks of an external passive coupling element like a ball lens or an aspherical lens is that it requires additional structures in the package to house the coupling elements. Again, the integration of these components requires precision assembly which comes at an additional cost of manpower and time. Moreover, it becomes necessary to study the alignment requirements of the stand-alone optical coupling elements at the transmitter and receiver side in great detail. Hence, the total cost of the system will be increased by the cost of additional coupling components, the cost necessary to model and fabricate the substrate to assemble these components. At the receiver side of the POF, coupling takes place from a large core diameter to a small area photo detector. If precision subassemblies and precise component placements are not employed, optical coupling with an external element at this point becomes a tedious task.

Plastic fiber with a lensed tip is a cost-effective coupling method for coupling light from the transmitter to the POF and from POF to the receiver [8], [9]. In this coupling scheme, the hemispherical lens fabricated at the tip of the fiber makes the system simple and efficient [10]. This eliminates precision subassembly and alignment, thereby lowering the manufacturing cost. In addition to this, it is seen that reflections and scattering are greatly reduced at transition surfaces in this hemispherical model since the lens and the fiber are of precisely the same material. Since POF has a large core radius, the hemispherical addendum will also have greater dimensions which will help to collect and focus light effectively at the ease of manufacturability. Besides, the device will be more mechanically stable and
less prone to shock and vibrations as external components are minimized.

The conventional lensed fiber fabrication methods include fiber grinding, wet etching, hot melting, etc. [11]–[13]. Since the core diameter of the plastic fiber is very high compared to its counterparts, it is easier to fabricate the hemispherical lenses at the tip. The manufacturing cost is lower since the fabrication is simple and does not require highly sophisticated equipment. This also gives the freedom to re-engineer the lens formed as and when it is required. The fabrication methods adopted are discussed in detail in the following sections.

III. POF MODELING, SIMULATION, AND ANALYSIS

Geometrical image analysis in ZEMAX software is an effective tool for computing the multimode fiber coupling efficiency. This analysis can generate the irradiance at any surface from an extended source with specific size and shape at the object surface. We have simulated the parameters of MH4001 Esaka fiber from Mitsubishi Rayon. The POF we modeled has a core diameter of 980 μm, cladding diameter of 1000 μm, and numerical aperture of 0.3. The core material is poly methyl methacrylate (PMMA) with an index of refraction 1.49. Simulations are done for direct coupling, fiber bends, light coupling with an external lens, and lensed fiber.

The direct coupling model, as shown in Fig. 1, involves a light source of 850-nm wavelength coupled to the input end of bare POF with flat ends, and the output of fiber is coupled to a detector of 50-μm radius. The simulations show a coupling efficiency of only 9.38%, which reflects the need for an additional coupling optics for the fiber. At this juncture, the two possible ways of improving the coupling efficiency is to use either an external discrete lens attached to the fiber or by making lens at the tip of the fiber.

To enhance the coupling efficiency, we amended the model by placing an external spherical ball lens between POF and detector. Since the diameter of the POF is large, a large ball lens is required for better light coupling to the detector, but as the size of the coupling lens increases the package dimensions also becomes larger. Various dimensions of ball lenses are evaluated and a tradeoff between the package size and coupling efficiencies are arrived at. Based on these studies, an optimum value of 2-mm radius lens is simulated and it yielded a power output coupling efficiency of 37.45%. Fig. 2 shows that a discrete large ball lens would achieve good coupling efficiency in comparison to the bare fiber, but this coupling scheme will increase the dimensions of the transceiver module since the ball lens radius is large compared to the dimensions of the fiber, which is undesirable.

On the other hand, a discrete ball lens of radius 0.48 mm, as shown in Fig. 3, would be a better fit since it will not increase the housing size required to hold the fiber-lens system. However, the difficulty is that the lenses of small radii have a shorter focal distance. A small radius lens can focus the beam to a nearer point at the expense of power output, while a large radius lens will focus at a longer distance from the lens, but maintain the power output to a high value. This can be observed with the fall in power to 18.81% in comparison to the larger lens radius coupling efficiency of 37.45%. Furthermore, using an aspherical lens to improve the coupling efficiency instead of a large ball lens, it becomes necessary to concentrate on the alignment and orientation of the lens in the module, which would require additional cost and effort, for the sake of increasing power output.

The following analysis discusses the proposed coupling method, namely the hemispherical structures integrated to both sides of the fiber, as shown in Fig. 4. Here, a plastic fiber of 0.49 mm radius is modeled with hemispherical ball lenses attached to both end of the fiber. The simulations yielded a higher power coupling efficiency of 85%. The power is concentrated in the 20-μm radius, and
Fig. 2. POF coupling using an external ball lens of radius 2 mm.

Fig. 3. POF coupling using an external ball lens of radius 0.48 mm.

Fig. 4. POF coupling using hemispherical lenses formed at the tip.
hence shifting of the fiber by 20 \mu m on either side of the detector will not affect the coupling efficiency of the system. Since the POF diameter is inherently large, the hemisphere’s radius is also large, thereby improving the spatial resolution of the image. Besides this, the whole system is spherically symmetric. This eliminates the need for orientation, unlike in the case of an aspherical lens.

An optimization algorithm is run for optimizing the radius of curvature of the lens. The radius of the integrated hemispherical lens is varied from 0.40 to 0.55 mm, to identify the optimum radius of the lens for the maximum output power coupling. A graph plotted with radius of lens curvature versus coupled power is shown in Fig. 5.

The results shown here reveal that the best case scenario for maximizing the power output is when the radius of the half lens at both ends is equal to the radius of the fiber. On either side of the radius, the output power drops sharply.

In the second optimization step, we analyzed whether the power output can be improved with a change in the refractive index of the hemispherical lens. It is observed that when the hemispherical lens is of the same material as that of the fiber, output power coupling is 85.445%. By increasing the refractive index 20% higher than that of the fiber, the power output can be increased to 88.67%.

IV. FABRICATION METHODS

Various methods have been reported in the literature for the fabrication of light coupling elements for POFs [14]. We have selected two fabrication methods based on the ease of fabrication and lower manufacturing cost.

The first method involves formation of the lens at the fiber edge by pressing the end face on a hot lens forming mold. The second method involves dipping the polished fiber tip in an optically transparent organic liquid [15]. The process of fabrication of a lens by hot melting method onto a fiber of plastic or glass origins would include the mechanical process of injection molding or compression [16]. The physical property of either a PMMA or perfluorinated polymer fiber and their lower fabrication temperatures have made the fabrication of lenses onto the fiber much easier. PMMA material is less dense with density range from 1150–1190 kg/m$^3$. This is less than half the density of glass which ranges 2400 to 2800 kg/m$^3$. More importantly, PMMA has higher impact strength than glass and does not shatter but instead breaks into large, dull pieces.

The hot plate method requires melting the fiber tip at its material melting point temperature and molding it with suitable cavity to form the lens. Based on the simulation results, we fabricated a die in steel material by precisely machining the required geometries, as shown in Fig. 6. Apart from this, the setup requires a hot plate to heat the mold and an arrangement to hold the POF vertically to the cavity. This simple fabrication setup and highly repeatable process makes the fabrication method cheap and attractive.

The steel mold is heated to the required temperature initially. The temperature of the mold is cross checked with the help of a thermocouple to reaffirm the required temperature level. Once the temperature reaches an approximate level of 150°C–160°C, the fiber is lowered towards the mold and allowed to take the shape of the mold. The fiber is subsequently allowed to cool to normal room temperature for 3–4 min. The fiber under microscopic view clearly shows the formation of a lens at the fiber tip, as shown in Fig. 7.

However, due to the small geometry of the mold cavity and the large diameter of the POF, the POF comes in contact not only with the semispherical cavity of the mold but also with the entire top surface of the steel structure. This makes the edges of the POF melt outwards, and it requires additional polishing.
Fig. 8. Lensed tip POF with polished edges.

Fig. 9. Hemispherical lens formed by polymer dipping.

Fig. 10. From flat polished POF.

Fig. 8 shows the fiber tip after polishing. Another phenomenon of the plastic’s behavior towards the heating and cooling process is the shrinkage of the fiber. Due to the lack of a surmountable pressure on the POF, the fiber warps and shrinks, this prevents the fiber in assuming the exact shape of the mold.

The second method describes a way of forming a spherical convex contour at the tip of POF by immersing the fiber in an optically transparent organic liquid and bonding this properly to the end face soon after the optical fiber is lifted from the liquid. The refractive index of the polymer material is matched to the refractive index of the POF core. In this process, the fiber tip is polished initially by mechanical polishing. Once the polishing is done, the fiber ends are cleaned and dipped to the polymer liquid. Now the fiber is taken out from the liquid and allowed to form the lens shape under surface tension. The shape of the lens depends on the viscosity of the liquid and the time given to settle down. Once the required shape is reached, the fiber tip is irradiated with UV light to make a proper adhesion. Many experiments have been carried out to optimize the required profile by using various viscous liquids and variable time for settling. The lens formed is as shown in the Fig. 9.

V. RESULTS AND DISCUSSIONS

The lenses formed by various methods are being characterized to evaluate its performance. The evaluation is done based on their effectiveness to converge the large spot size of POF output to a considerably smaller spot size and hence to improve the coupling efficiency. Initially, the POF with lensed tip is illuminated with the light at the 850-nm wavelength. The distance from the beam profiler is adjusted in such a way that the output beam spot is reduced to the minimum size possible. Now the lensed POF is replaced with a flat polished POF, and the output spot is captured at the same distance using beam profiler. The output spot size profile for a flat polished POF and lensed POF formed by polymer dip method are as shown in Figs. 10 and 11.

The captured spot sizes at 1.6-mm distance from the profiler are compared, and it clearly shows a reduction in the spot size of the order of one-fourth of the original dimension. The coupling efficiency has improved by 27% with the lensed fiber fabricated. The experimental result shows that there is a major variation from the output spot size predicted by simulation. The light beam is not converging to the smaller dimension, and hence the coupling efficiency is much below the expected value. As per our understanding, the minor variations in the lens parameters cannot be responsible for such a larger deviation in the coupling efficiency.

Closely analyzing the results, it is realized that the initial simulations are done assuming that the fiber is straight, an ideal state. It did not include any fiber bends, but in the real case, the fiber has random bends. In addition, the lens structure at the input side generates a restricted mode launch condition under center launch conditions. Due to these factors, straight fiber status and restricted mode launch conditions, light is confined to the lower order modes lying at the center of the core which results in a lower divergence beam exit [17]. Under the random bends, all possible fiber modes are excited, and this leads to larger divergence and hence a larger beam size at the exit.

In order to verify this fact, we modeled the same lens under bend fiber conditions. This resulted in a lower coupling efficiency of 34%, which very agrees well with the experimental results under the fabrication limitations.

The lenses fabricated with the hot melting method did not show a better convergence, as the lens curvatures could not be controlled since the whole fiber tip was getting deformed during the fabrication process. A new mold with wider aperture is being considered to avoid these problems. Another concern is that, if the molded portions are not allowed to cool down properly, instead of a perfect smooth spherical surface, a lot of fiber “hairs” will be formed. This reduces the lensing effect and further polishing is required to make the surface perfect. In this case, the polymer dip method seems to be much better for the fabrication of lensed POFs. The variables for optimization vary with the liquid properties and the final lens shape to be fabricated.
VI. CONCLUSION

We have analyzed various cost-effective coupling methods for POF communication by optical simulations. The simulations showed an improved light coupling efficiency with the lensed POF. The lensed tips are realized using hot blowing and polymer dip fabrication techniques. The experimental evaluation of optimized lens structures resulted in an improved coupling efficiency of 27%. It is also eminent that the fiber bends play an important role in deciding the actual divergence of the beam at the exit end. The variation of light coupling efficiency from the simulation results are attributed to the higher order mode excitation and divergence associated with the fiber bends. Therefore, it is advised to take care of this fact while designing the coupling optics. Comparing the two fabrication methods, the polymer dip method is preferred over the hot blowing technique. Another added advantage of this method is that it can be used to fabricate lenses of any refractive index.

In general, the use of lensed POF improves the coupling efficiency, reduces assembly costs, and also helps to maintain the package dimensions to minimum. They also offer ease of installation and altogether become a cost-effective solution for POF communications.

REFERENCES

Than Aye Aung, photograph and biography not available at the time of publication.

Xiao Yongfei, photograph and biography not available at the time of publication.

Pamidighantam V. Ramana, photograph and biography not available at the time of publication.

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