Novel Fiber Fused Lens for Advanced Optical Communication Systems

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ABSTRACT

We report on a novel fused collimator design as part of a transmitter optical sub-assembly (TOSA) used for agile microwave photonic links. The fused collimator consists of a PM fiber that is laser fused to a C type lens. The fusion joint provides a low loss interface between the two components and eliminates the need for separate components in the optical path. The design simplifies the number of components with the optical assembly leading to several advantages over traditional designs. In this paper we use the fiber coupling efficiency as a design metric and discuss the opt-mechanical tolerances and its effect on the overall design parameters.

Keywords: Fiber Collimators, Fiber Coupling, RF Photonic Links, TOSA

1. INTRODUCTION

Recent advances in the development of high power 1550nm semiconductor lasers for agile microwave photonic links have created a demand for high performance, reliable and robust beam delivery optics. In this paper we describe a transmitter optical sub-assembly (TOSA) based on a novel collimator design. The basic elements of the TOSA are the laser source, precision molded asphere, isolator, focusing lens and PM fiber. Traditionally, the focusing lens and fiber are discrete elements. In this application, the focusing lens and optical fiber are fused together to produce a single element referred to as a collimator (although in this application it's used as a coupler). The collimator consists of a small plano-convex fused silica rod lens also known as a C-lens which is laser fused to the optical fiber. Apart from the advantage of having a fewer number of discrete elements the fused collimator offers the advantage of a more robust assembly, reduced risk of damage to the fiber and reduced return loss. The laser fusion process leaves a monolithic structure that has virtually no residual stress or noticeable interface. Preliminary results based on the coupling efficiency for light from the source into the fiber are 77% (90% without the isolator); a PER (Polarization Extinction Ratio) of > 25dB and laser RIN magnitude of < -165 dB/Hz. This is the first time to our knowledge such a device is used in this type of application.

2. DESIGN CONCEPT

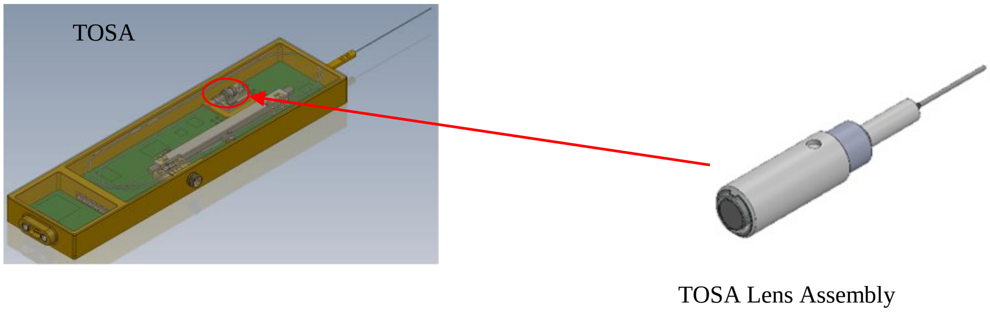

Figure 1: RF Transmitter Package.

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The TOSA forms part of a larger Kovar package which houses the light source, electronics, modulator, and RF circuit. The low CTE of Kovar (iron-nickel-cobalt alloy) makes it especially suitable for applications that require very low thermal expansion. As the CTE is well matched to the expansion of other materials (e.g., snout/tube and lid), this helps to ensure high performance over an extended temperature range (-40°C to 85°C) for a compact form factor TOSA. The alignment of the lens assembly to the light source, and the attachment of the lens assembly to the package are critical attributes to ensure performance and manufacturability. The lens must be quickly and easily positioned relative to the light source to ensure optimal coupling and the attachment of the lens to the package housing must prevent or minimize movement during operation, including random vibration and shock up to 20G. Dimensional tolerances of the mechanical components are minimized to help ensure consistency in the design and assembly, and limiting these in the optical path is critical for the highest coupling efficiency. Reducing the complexity of the actively aligned components helps ensure a cost-effective design while providing high performance and high coupling efficiency.

The performance of the module is impacted by the light source (laser) Relative Intensity Noise or RIN. RIN depends on many quantities, including, temperature, frequency, output power, side mode suppression ratio (SMSR), relaxation oscillation frequency, and optical feedback. The major source of RIN is typically spontaneous emission. RIN is greatly influenced by optical feedback so the discontinuities in the optical path, primarily the lens, must be minimized to enable high performance. Since the laser has been well characterized with a RIN < -170 dB/Hz, the components in the optical path (i.e., lens) will contribute to the RIN of the entire assembly.

3. COUPLING SCHEMES

Various schemes exist for coupling light from a source into a fiber. The type of lens used greatly depends on the source size and beam divergence. For single mode fibers, achieving a high coupling efficiency requires that the optical field matches well to the mode field of the optical fiber. Additionally, aberrations associated with the lens cause the optical field to become distorted leading to increased power loss, thereby, severely reducing the coupling efficiency. Both theoretically and experimentally, different coupling schemes have been studied using single and multi-element lenses. The simplest scheme using a spherical singlet lens tends gives reasonable coupling efficiencies for sources having a low numerical aperture (NA). Other designs employing lenses having more complex surfaces, for instance aspheres tend to give better efficiency, especially for sources having a higher NA. In order to adequately correct for the lens aberrations multi-element schemes are used that achieve close to 100% coupling efficiency. However, as the number of individual elements increases the difficulty in achieving good alignment between the various elements becomes challenging. Mechanical parts require tighter tolerances to preserve the optimum position for the various elements leading to increased cost for mechanical components. One goal of this paper is to show how dimensional tolerances for the mechanical design influence the optical source to fiber coupling efficiency. In particular, we show that the use of a novel fused fiber collimator reduces the mechanical design complexity and provides a path for achieving high coupling efficiency over more traditional schemes.

4. FUSED FIBER COLLIMATOR

The collimator is a monolithic structure where a plano-convex rod lens (C-lens) is laser fused to a PM fiber. The fiber fusion process was a pioneering technology developed and patented by LightPath. Although the process has been reported elsewhere [1], a brief description is presented.

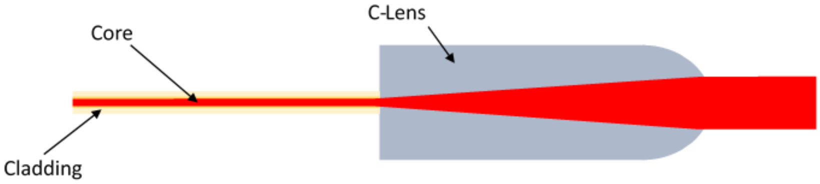

Figure 2: Fiber Collimator design.

In the fusion process, the fiber is cleaned, stripped of its outer jacket and cleaved. The cleaved end is brought in close proximity to the flat side of the C-lens. A carbon dioxide laser is activated and, in combination with galvo mirrors, creates a circular localized heated zone at the fiber-lens interface. Both materials reach melting point, and are fused together while cooling. The resulting interface is a monolithic structure that has no noticeable interface between the fiber and lens, and no appreciable residual stress. For polarizing maintaining fibers, this process is capable of achieving a polarization extinction ratio (PER) of >30dB. The high PER value demonstrates negligible residual stress birefringence resulting from the fusion process. The fusion joint maintains a pull strength in excess of 400MPa, and demonstrates a high degree of mechanical stability.

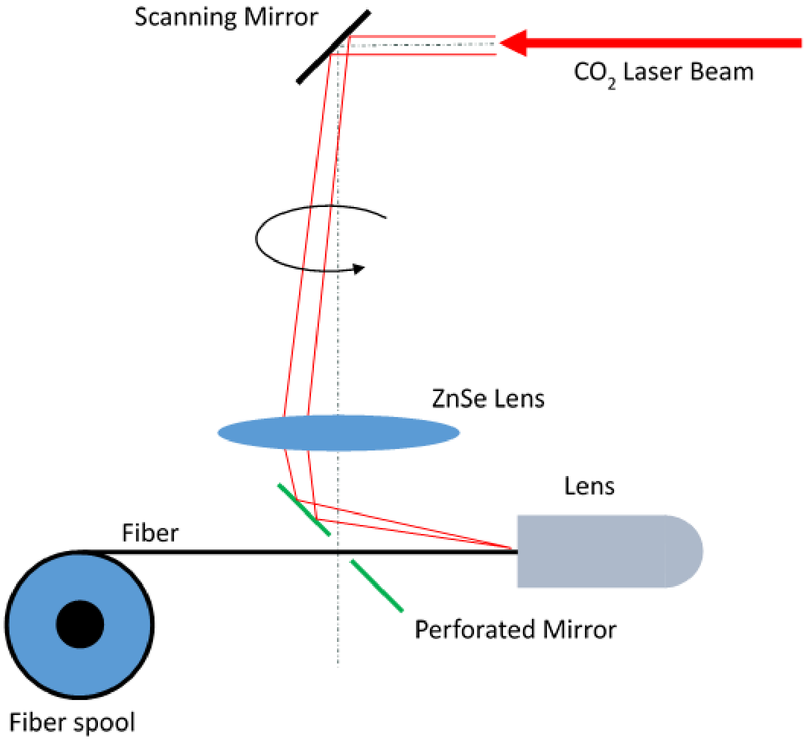

Figure 3: Laser Fusion Process.

5. OPTICAL LAYOUT

Figure 4 shows an illustration for the TOSA. The source is a Buried Heterostructure quantum well semiconductor DFB laser capable of generating up to 200mW of polarized light. Due to better current confinement and careful design of the semiconductor wafer fabrication process, the laser gives a low RIN figure < -170 dB/Hz, [2]. The precision molded asphere collimates the light, which then passes through a magnet-free latched garnet, dual-stage optical isolator and is focused and coupled into the optical fiber by the fused collimator.

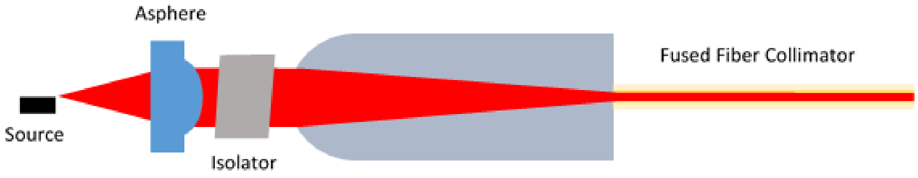

Figure 4: Basic elements of the TOSA.

6. OPTICAL SIMULATION

We used the optical simulation software Zemax to calculate the coupling efficiency for the TOSA. The coupling efficiency is calculated using the overlap between the mode field in the fiber and the focused Gaussian as:

$$T = \frac{\left| \iint F_r(x,y) W^*(x,y) dxdy \right|^2}{\iint F_r(x,y) F_r^*(x,y) dxdy \iint W(x,y) W^*(x,y) dxdy} \qquad (1)$$

Where $F_r(x, y)$ is the function describes the complex amplitude of the fiber, $W(x, y)$ is the function describing the complex amplitude of the beam and the * symbol represents complex conjugate [3].

The C-lens design (radius and center thickness - CT) is optimized to maximize the coupling efficiency of light from the source to the fiber. The optimization was performed in Zemax using the Physical Optics Propagation algorithm. Since the beam is largely collimated in the space between the asphere and collimator C-lens, it was deemed that the effect of the isolator on the beam wavefront was negligible. This greatly simplified the optical setup and accelerated the optimization. The distance between the collimating lens and the source is set to the lens working distance of 244μm. The nominal beam size ($1/e^2$) exiting the asphere is an ellipse with major and minor axes of ~ 1102 x 860μm (ellipticity of 78%). At this distance the light is collimated with a transmission close to 99%. The light is then coupled into the fiber by the fused fiber collimator giving a predicted coupling efficiency of 91%.

In order to reduce back reflections, an isolator was inserted between the asphere and collimator. The isolator sits at a slight angle of 4°. Due to the 4° tilt, the beam walk-off after the isolator is 50μm. However, the walk-off is partly compensated by the C-lens, whereby, the final beam displacement at the fiber-lens interface is estimated to be around 0.5μm. Given that the mode field diameter (MFD) for the fiber at 1550nm is around 10μm, the coupling loss due to the beam walk-off was modeled to be only 3%. The overall coupling efficiency was modeled to be around 84%. The difference in coupling efficiencies between the model with and without the isolator is attributed to the transmission loss (Fresnel reflection loss due to the number of surfaces that makeup the isolator) and the beam walk-off.

7. MECHANICAL DESIGN

The mechanical parts consist of a short lens holder for the aspheric collimating lens, a casing for the collimator lens and a main collet for the optical components. Strain relief is added for the fiber in the form of an epoxy cone and a stainless steel tube, added to provide support for the fusion joint. Due to the ease of machining and cost, the initial prototypes for the lens holder, collimator housing and main housing were fabricated from brass. The final design material would be Invar because of its low thermal expansion and material compatibility of the module.

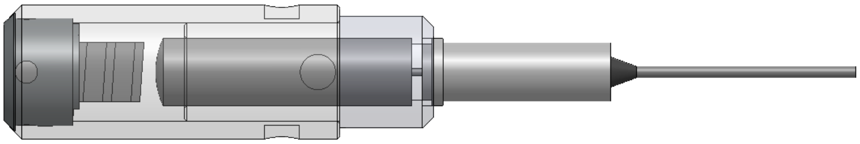

Figure 5: Mechanical design for the TOSA.

Tolerances for the machined parts were determined from relevant functional requirements. In this case, the maximum and minimum tolerance values for each of the mechanical parts were determined based on the influence on the overall coupling efficiency. Tolerances based on lens dimensions (mainly the lens CT and radius error) gave no noticeable change in the overall coupling efficiency compared with individual element tip/tilt and decenter. When mechanical parts are assembled, the amount of engagement between mechanical surfaces plays a crucial part in specifying tolerances. Elemental tip/tilt tends to have a greater effect than decenter. Elemental tip/tilt errors related to how well the lens engages with its holder. As an example, the front lens assembly has the least amount of engagement of the mechanical surfaces due its shorter length and is more likely to have a greater tilt during assembly compared with the collimator housing or main housing, which have a substantially longer engagement. Considering the differences between the outer diameter (OD) for the asphere and the inner diameter (ID) for the lens holder we determined that the asphere could tilt up to a maximum angle of 5.5° for a 25μm difference in tolerance between the lens and the holder.

In order to investigate the effect on the coupling efficiency, the aspheric lens was tilted by 5.5° and decentered by ±10μm in both X and Y. The coupling efficiency was modeled by optimizing the collimator position in both X/Y and its tilt (see Table 1). The values indicate that although the coupling efficiency could be recovered, this required a relatively large positional/angular change for the collimator. Given the restrictions on the main housing, ideally we desired a tilt error 10 times less or 0.55° making the difference in tolerance between the lens and the holder 2.5μm. This would reduce the coupling efficiency by ~ 5%. However, realistically, the best achievable tolerance was 12μm resulting in a maximum tilt error of 2.7°.

Tolerance error type	Magnitude of error	Decenter on C-lens only	Decenter / tilt on C-lens	Final Coupling efficiency
Tilt on asphere	5.5°	-380μm	-227μm/5°	82%
Tilt on asphere	2.7°	-185μm	-51μm/4.3°	84%
Decenter on asphere	± 10μm in both X & Y		-30μm in Y & -0.606° in X	84%

Table 1: shows the effect of a 5.5° and 2.7° tilt on the asphere.

As was mentioned previously, the CT was optimized to maximize the coupling efficiency. As before, if we consider the tolerance between the lens OD and holder ID as 25μm, due to the longer engagement the maximum tilt for the C-lens is only 0.25° - well within our desired tilt error of < 0.55°.

8. EXPERIMENTAL RESULTS

Laser relative intensity noise can be a limiting factor in the transmission of signals, by reducing the signal-to-noise ratio and increasing the bit error rate, thus reducing performance. Laser RIN can vary significantly depending on the properties of the laser and back reflections. As mentioned earlier, the DFB lasers were previously characterized and the RIN performance analyzed. A total of six assemblies were built. For one of the assemblies, we measured the beam exiting the assembly after the isolator, which was 1153 x 850μm with an ellipticity of 74%. Compared with the simulation, there was good agreement between the simulated and measured results. However, there was a slight reduction in the beam quality with the isolator, mainly along the major axis, which was not predicted in the model. With the isolator, the maximum efficiency achieved was 77%. Without the isolator, the efficiency was 90% - within 1% of the model's predicted efficiency.

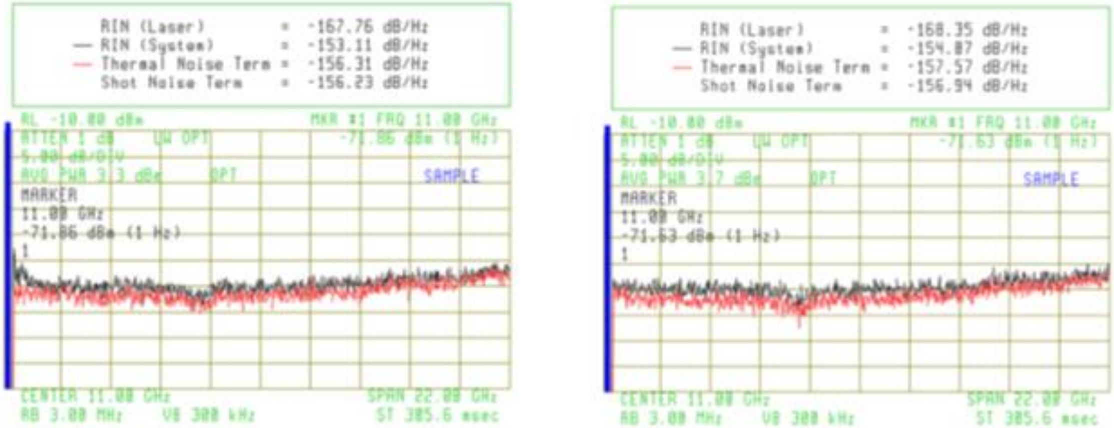

Figure 6: Laser RIN measurements.

RIN measurements were performed using the lens assembly. The image on the left of Figure 6 shows laser RIN at -167.76 dB/Hz. Using the same light source, a separate lens assembly was measured with RIN of -168.35 dB/Hz (right image of Figure 6). Further measurements show RIN of -168 dB/Hz with a laser bias of 300 mA and 400 mA with 53 mW and 65 mW of optical output power respectively.

9. CONCLUSIONS

Tolerances play a large part in any precision assembly process and the relative precision influences cost and manufacturability. In this paper, we have considered the tolerance errors for the optical and mechanical components and examined the influence on the coupling efficiency, leveraging this information for a more complete cost versus benefit analysis. We have shown that the fused fiber collimator is less sensitive to mechanical tilting than the asphere lens due to its longer engagement. As the fiber is fused to the C-lens, the lens assembly reduces the number of discreet elements, greatly simplifying the final assembly where active alignment of multiple components impacts the higher coupling efficiency.

The highest coupling efficiency without the isolator predicted by the model was 91%, which agreed well with measured coupling efficiency of 90%. With the isolator, the model predicted a maximum efficiency of 84%. The highest achievable efficiency with the isolator was around 77%. We believe the discrepancy between the modeled and measured results is primarily due to a higher than expected transmission loss through the isolator and possible surface quality of the optical isolator. Our RIN measurements of two devices show the laser RIN noise is -170dB/Hz and -168dB/Hz, indicating that there is no significant optical feedback from the TOSA.

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