Optimum mechanical splice conditions for fiber with hole-assisted structure

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Abstract: The mechanical splice characteristics of a hole-assisted fiber (HAF) are investigated both numerically and experimentally. We successfully derived the optimum mechanical splice conditions, which can be universally utilized for HAF with arbitrary structural parameters.

OCIS codes: (060.2330) Fiber optics communications; (060.2340) Fiber optics components

1. Introduction

Recently low bending loss fiber has been researched intensively because it is expected to lead to improved fiber handling and a reduction in the currently required work and storage space [1]. Hole-assisted fiber (HAF) has a germanium doped core with several air holes. By designing the fiber structure appropriately, HAF has both a comparable mode field diameter (MFD) to single-mode fiber (SMF) and a low bending loss characteristic [2]. Meanwhile, optical fiber interconnection methods such as fusion and mechanical splicing are important for optical fiber network systems [3]. The conventional fusion splice method can easily be utilized for HAF since it has a conventional doped core. By contrast, the mechanical splicing of HAF causes problems since the liquid refractive index matching material that is employed penetrates the air holes, and the splice characteristics degrade with the penetration length and refractive index of the index matching material [4]. To prevent the index matching material from penetrating the air holes, we have proposed a mechanical splicing method that employs a solid index matching material, and clarified its effect on the mechanical splice characteristics of the HAF [5]. However the relationship between the mechanical splice conditions and the structural parameters of HAF remains unclear.

In this paper, we investigate the mechanical splice characteristics of HAF both numerically and experimentally. Our results show that by optimizing the mechanical splice conditions we can realize good splice characteristics without any need to consider the structural parameters of the connected HAF.

2. Discussion model

Figure 1 (a) shows a cross-sectional image of an HAF and (b) shows a schematic image of a mechanical splice point. We assumed a germanium doped core with a radius a and a relative index difference Δ. N air holes of diameter d were considered, and they were located with a distance R between the core center and the air hole edge. Here we defined an air filling fraction $S \equiv N\pi(d/2)^2/(\pi(R+d)^2 - \pi R^2)$ as the ratio of air hole area between the outer and inner circles around the air holes. Also, at an HAF connection, we assumed that index matching material with a relative index difference of Δ_h penetrated all the air holes equally to a length z. This formed asymmetrical parallel waveguides, and mode coupling between the core and air holes with index matching material leads to additional splice loss [6]. Here we defined the ratio of the relative index difference of the index matching material to the core Δ as $R_\Delta \equiv \Delta_h / \Delta$.

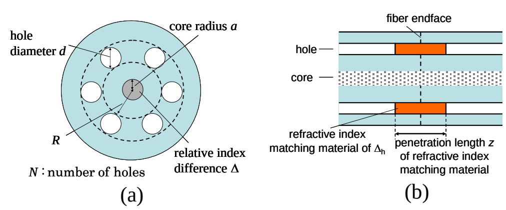

Figure 1. Splice model.(a) a cross-sectional image of HAF, (b) schematic image of mechanical splice point.

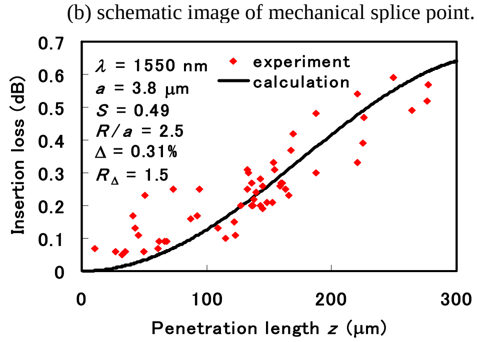

Figure 2. Relationship between penetration length z and insertion loss.

Figure 2 shows the relationship between the penetration length of the refractive index matching material into an air hole and the insertion loss. Here we assumed λ = 1550 nm, a = 3.8 μm, S = 0.49, R/a = 2.5, Δ = 0.31%, and R_Δ = 1.5. The plots and the solid line show measured and calculated results, respectively. Figure 2 confirms that these results have a similar tendency. We also confirmed that the measured splice losses are slightly larger than the calculated values. This is due to the existence of a lateral offset loss, and we can estimate the average lateral offset in our experiments as 0.1 dB by utilizing least mean square fitting with the measured results.

3. Results and discussion

First, we examined the relationship between the V-parameter of the core and the mode-coupling loss α. Figure 3 shows the calculated V-parameter dependence of α at 1625 nm. Here, the N, S, and R/a values of the HAF were assumed to be 6, 0.5, and 2, respectively. The mechanical splice conditions of z and R_Δ were set at 100 μm and 1, respectively. The solid, broken, and dotted lines show the results when the MFDs without the air holes were 8, 9, and 10 μm at 1310 nm [7]. The α value increases as the V-parameter and MFD decrease. In general, the MFD of HAF is related to the R/a value, and an R/a of 2 or more enables us to reduce the MFD suppression to 10% or less by adding the air holes [2]. Thus, we can discuss the α value of HAF more easily by taking account of the V-parameter of the core and its initial MFD characteristic.

We then investigated the relationship between α and the structural parameters of the air holes. Figure 4 shows the relationship between S and α calculated at 1625 nm. The N, MFD, and R/a values were set at 6, 9 μm, and 2, respectively. The mechanical splice conditions of z and R_Δ were 100 μm and 1, respectively. The solid, broken, and dotted lines show that the results for the V-parameters were 2, 2.2, and 2.5, respectively. It can be seen from Fig. 4 that α varies sinusoidally as a function of S. This is because the variation in S also changes the hole diameter, and this causes the variation in the mode coupling condition in terms of the difference in the propagation constant [6].

We then defined the S_{max} at which α reaches its maximum value for each V-parameter to consider the worst-case mechanical splice for HAF. We also assumed an allowable maximum α of 0.05 dB, and set the corresponding allowable maximum penetration length at z_{max}. Figure 5 shows the relationship between the V-parameter and z_{max} calculated at 1625 nm when S was designed to be S_{max}. Here, MFD and R_Δ were 9 μm and 1, respectively. The solid, broken, and dotted lines show the results when N was 6, 8, and 10, respectively, with R/a = 2. The broken lines with one dot and two dots, respectively show the results when R/a was 2.5, 3 with N = 6. In this figure, the mode-coupling loss becomes less than 0.05 dB when z_{max} becomes smaller than the values shown by each of the lines. Figure 5 confirms that z_{max} decreases as the V-parameter and R/a decrease. It is also seen that z_{max} is almost independent of

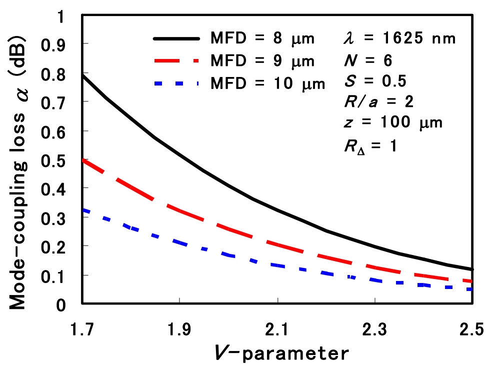

Figure 3. Relationship between V-parameter and mode-coupling loss α.

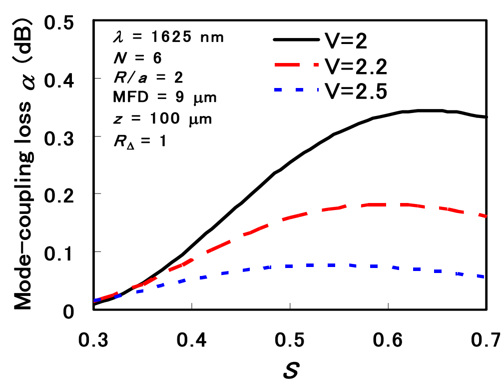

Figure 4. Relationship between S and mode-coupling loss α.

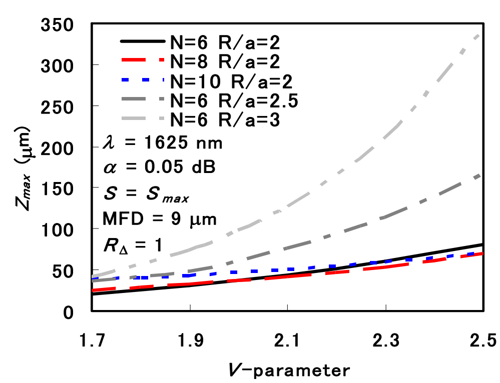

Figure 5. Relationship between V-parameter and z_{max}.

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the number of air holes. Thus, Fig. 5 reveals that the mechanical splice condition of z_{max} can be derived by taking account of the *V*-parameter of the core and the *R*/*a* of the HAF.

A HAF with *R*/*a* = 2.5 was prepared for experimental verification. The *V*-parameter of the initial core can be estimated to be 2.1 from its core radius and Δ. The *N*, *S*, and MFD values of the HAF at 1310 nm were 6, 0.49, and 9 μm, respectively. Then, we can estimate the R_Δ to be 1.5 taking account of the refractive index of the solid type matching material. Therefore Fig. 5 indicates that we can expect the mechanical splice loss of the HAFs to be 0.15 dB or less if we can control the penetration length *z* to 60 μm or less. The measured average mechanical splice loss of 30 samples was 0.11 dB at 1550 nm, and the results show the validity of our mechanical splice conditions for HAF. However, we also confirmed experimentally that the maximum penetration length reached 100 μm. Moreover, Fig. 5 also reveals that a z_{max} of 30 μm or less will be required when *V*-parameter becomes 1.7.

Then we examined the relationship between R_Δ and z_{max} at *V* = 1.7. Figure 6 shows the relationship between R_Δ and z_{max} calculated at λ = 1625 nm. Here we assumed that α = 0.05 dB, $S = S_{max}$, *R*/*a* = 2, and MFD = 9 μm. The solid, broken, and dotted lines show the results obtained for *N* = 6, 8, and 10, respectively. Figure 6 indicates that z_{max} greatly increased as R_Δ decreases. An R_Δ of 0.3 can increase z_{max} to 100 μm or more. Here, R_Δ affects the return loss characteristic as well as the splice loss. A return loss of more than 40 dB is usually required. Moreover, the refractive index of the index matching material has a negative temperature coefficient. These requirements result in a temperature coefficient of -2.2×10^{-4} or more [4] when we set R_Δ at 0.3 and assume an environmental temperature range of -40 to 75°C. As a result, we conclude that we can expect to realize superior mechanical splice characteristics by optimizing the refractive index and temperature coefficient for the maximum penetration length of the index matching material, which should be a solid type. Moreover, the derived mechanical splice conditions will be valid for HAF with arbitrary structural parameters because we considered both the *V*-parameter and *S* dependences.

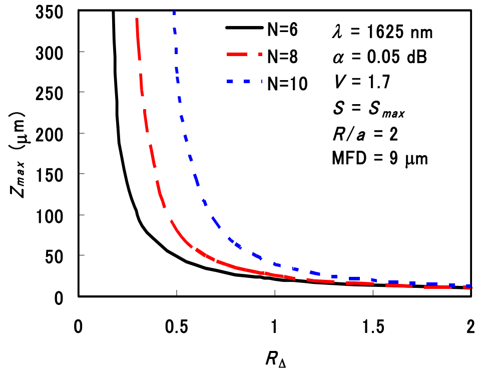

Figure 6. Relationship between R_Δ and z_{max}.

4. Conclusion

We investigated the mechanical splice characteristics for HAF both numerically and experimentally. We showed that satisfactory mechanical splice characteristics can be expected by optimizing the refractive index and temperature coefficient for the maximum penetration length of a solid index matching material. The derived splice conditions can be used for HAF with arbitrary structural parameters because we took account of the HAF dependence on *V*-parameter and *S*. We believe that our results will be useful for expanding the application area of HAF, which can provide attractive characteristics.

5. References

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