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Analysis of single-mode optical fiber splicing loss in telecommunications network systems

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ABSTRACT

This paper investigates the impact of angular misalignment on splice loss across five distinct types of single-mode fiber (SMF), a critical factor in optical fiber network reliability. We regularly analyze splice loss at misalignment angles ranging from 0.1° to 1°, evaluating performance at both 1310 nm and 1550 nm wavelengths. Our findings consistently show that increasing angular misalignment directly causes a significant increase in coupling loss, with the SMF-28e+ showing the lowest susceptibility, recording losses of 0.7299 dB at 1310 nm and 0.672 dB at 1550 nm for a 1° angle. These detailed insights into the angular misalignment tolerance of various SMF types is crucial for enhancing the design and deployment of robust and efficient optical fiber networks, ultimately minimizing signal degradation and improving overall network performance.

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1. INTRODUCTION

The relentless advancement of communication technology has firmly established fiber optic-based systems as the bedrock to support the burgeoning demand for high-speed and large-capacity data transmission [1]. Recent technological innovations continue to improve the performance of optical fiber systems, including the integration of new materials and fiber designs [2].

Optical fiber inherently offers compelling advantages, including robust immunity to electromagnetic interference, an expansive bandwidth, and the capability for low-attenuation light signal transmission across considerable distances. This underscores that splice loss performance is a complex interaction between MFD and fiber profile, not merely wavelength [3]. Within the spectrum of optical fiber types, SMF stands as the preferred choice in contemporary communication systems. Its ability to transmit light signals in a singular mode significantly mitigates mode dispersion, thereby bolstering transmission stability and fidelity [4].

The inherent characteristics of SMF render it exceptionally well-suited for long-haul communication networks, primarily due to its diminutive core diameter which facilitates a more direct light propagation path with minimal signal degradation [5]. However, the splicing of SMF exhibits a notable vulnerability to geometric misalignments, which can induce substantial splicing losses and consequently compromise signal integrity [6]. These splice losses typically stem from disparities in mode field diameter, angular deviations, the presence of gaps between fiber end faces, and contamination [7]. Fusion splicing has been demonstrated to produce lower insertion loss compared to mechanical splicing, especially in commercial networks such as those studied at PT. Telkom Indonesia [8].

In an era increasingly focused on energy efficiency and system sustainability, achieving precise fiber optic splicing has become paramount for minimizing power dissipation and reducing the frequency of network maintenance [9]. Consequently, sophisticated modeling and simulation techniques, often employing software such as OptiFiber, are instrumental in predicting and mitigating splice losses prior to physical deployment. This proactive approach yields significant benefits in terms of time savings, cost reduction, and energy conservation [10].

This study focuses on analyzing splicing losses caused by angular misalignment in several commonly used types of SMF. The simulation results are expected to provide technical insights to enhance the reliability and efficiency of optical fiber-based communication network systems.

2. THEORETICAL REVIEW

SMF can effectively mitigate signal interference and modal dispersion, enabling higher data transmission speeds and extended reach compared to multimode fibers. While SMFs offer superior stability and reliability, their requirement for light sources with narrow spectral linewidths generally makes them more expensive.

MFD is a crucial parameter defining the effective optical power distribution within the SMF core. Discrepancies in MFD between two spliced fibers can lead to a mismatch in optical field distribution, subsequently causing significant splice loss. Fibers with larger MFDs are generally more susceptible to angular misalignment, which can exacerbate coupling efficiency issues. The mode field diameter for each fiber type was validated using standard MFD measurement techniques [11].

Splice loss represents the power loss incurred when two optical fibers are permanently joined. The refractive index values used in this simulation are consistent with the specifications provided by leading fiber manufacturers such as Corning [12]. This loss primarily arises from imperfections in the splice, such including differences in core size, variations in refractive index, or misalignments in angular position. For SMF, angular misalignment is a significant contributor to power loss by deviating light propagation and reducing coupling efficiency [13]. A widely adopted theoretical approach to quantify splice loss, particularly due to angular misalignment, is the model proposed by Miller and Kaminow (1988). This model assumes a near-Gaussian power distribution for light propagating within SMF, allowing splice loss to be calculated based on the degree of mismatch between the Gaussian modes of the two fibers being joined. The equation for calculating splice loss (α_{splice}) in decibels (dB) is given by:

$$\alpha_{splice} = -10\log\left[\left(\frac{16{n_1}^2{n_2}^2}{(n_1+n_2)^4}\right)\frac{\sigma}{q}e^{\frac{\rho u}{q}}\right] \quad (1)$$

In this equation, n_1 and n_2 denote the refractive indices of the fiber cores. The parameter σ represents the ratio of the mode field diameters (w_1 and w_2) of the two fibers, while ρ, q, and u are complex parameters encompassing transversal offset (x), longitudinal offset (z), and the angular misalignment (θ). A clear understanding of this theoretical model is essential for analyzing and validating the simulated splice loss results, particularly concerning angular variations, aiming to ensure maximum transmission efficiency in optical fiber systems.

3. METHODOLOGY

This study employs a simulation-based approach, meticulously executed using OptiFiber software, to analyze the precise characteristics of SMF resulting from angular misalignment within typical telecommunication network systems. The investigation comprehensively evaluates system performance at two critical communication wavelengths 1310 nm and 1550 nm. Angular misalignment, a key parameter influencing splice integrity, was regularly varied across a range from 0.1° to 1°.

Within the OptiFiber environment, a detailed model of two interconnected SMF segments was constructed. These fibers were accurately represented using standard SMF specifications, incorporating typical physical parameters such as core diameter, cladding diameter, and numerical aperture, thereby replicating realistic fiber splicing conditions. Optical signals were then separately injected into this model at the designated wavelengths. To assess the impact of angular deviation, a series of distinct misalignment angles, ranging from 0.1° to 1° with regular increments, were configured as individual simulation scenarios. For each specific combination of wavelength and angular misalignment, OptiFiber automatically calculated and outputted the resultant splice loss values, expressed in decibels (dB).

The acquired splice loss data from these simulations underwent comprehensive analysis. This analysis aims to identify inherent patterns and trends in splice loss as angular misalignment increases, examining these behaviors distinctly for both 1310 nm and 1550 nm wavelengths. A direct comparison of splice loss values between these two wavelengths was performed at every level of misalignment to ascertain their respective susceptibilities or robustness to angular deviation. Finally, the simulated splice loss results were graphically represented, illustrating splice loss (Y-axis) against angular misalignment (X-axis) for both wavelengths, which facilitated clear and intuitive interpretation of the experimental outcomes. This methodical approach enabled a thorough and quantitative evaluation of the interdependent effects of angular misalignment and wavelength characteristics on SMF splice loss through a controlled simulation environment.

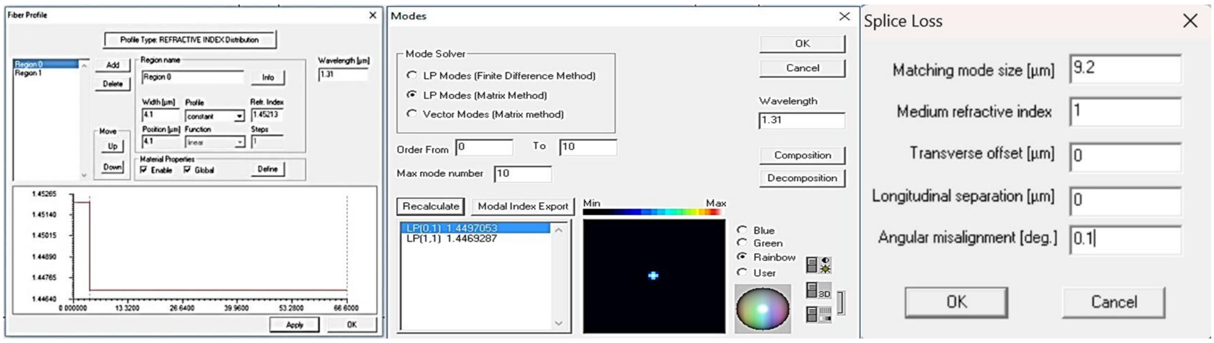

Figure 1. Visualization of configuration stages for optical fiber splice loss simulation.

The optical fiber structure was meticulously modeled via OptiFiber's Fiber Profile feature (Figure 1), manually configuring the refractive index profile with constant layer indices for core (4.1 µm radius) and cladding (62.5 µm radius). These parameters, based on silica doped with germanium and fluorine, and refractive index values were defined at 1.31 µm wavelength to ensure valid single-mode propagation, consistent with industry standards [11]. Operating wavelengths were then set at 1310 nm and 1550 nm. OptiFiber was selected for its robust numerical methods, including FEM-based mode solvers for accurate modeling of fiber properties and electromagnetic field distributions

4. RESULTS AND DISCUSSION

This aligns with findings that angular deviation reduces optical mode overlap and increases radiation loss [14]. Notably, SMF-28e showed the highest loss, while SMF-28e+ performed best among the five Commercially relevant SMF types studied, suggest that fiber structural properties like core-cladding refractive index contrast influence misalignment sensitivity. Furthermore, the simulations reveal significant differences in splice loss across fiber types and wavelengths, with generally lower losses observed at 1550 nm. This is attributed to the larger mode field diameter at this wavelength, which maintains greater optical field overlap even with slight angular deviations [15].

These findings underscore the critical importance of judiciously selecting the appropriate fiber type and meticulously maintaining splice angle accuracy during field installations. The adoption of automated fusion splicers equipped with high angular tolerance and real-time field mode monitoring capabilities is strongly advocated to minimize splice loss. Furthermore, strict adherence to established maximum splice loss thresholds, such as 0.1 dB limit specified by Telkomsel and the ITU-T G.652.D standard, is paramount for preserving the efficiency and reliability of contemporary optical transmission systems [16, 17].

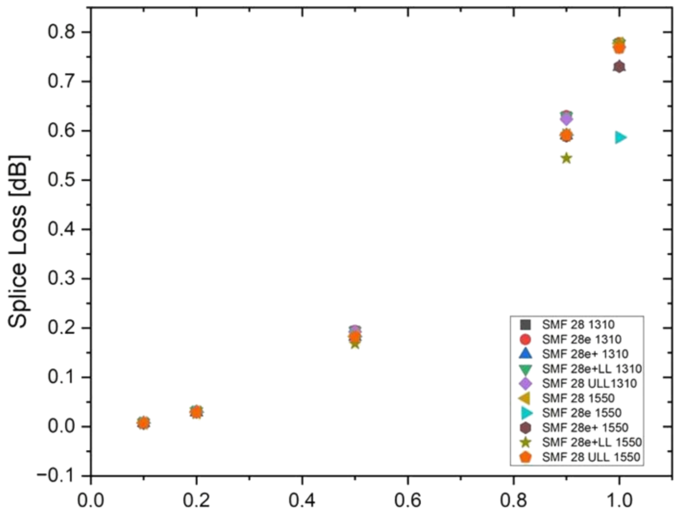

Figure 2. Splice loss at a wavelength.

Table 1. Splice loss values at a wavelength of 1310 nm.

Angular (°)	Splice loss (dB)				
	SMF 28	SMF 28e	SMF 28e+	SMF 28e+LL	SMF 28ULL
0.1	0.0077	0.0078	0.0073	0.0077	0.0077
0.2	0.0311	0.0311	0.0292	0.0311	0.0308
0.3	0.0699	0.0700	0.0656	0.0699	0.0693
0.4	0.1244	0.1245	0.1167	0.1243	0.1236
0.5	0.1942	0.1946	0.1824	0.1942	0.1925
0.6	0.2790	0.2802	0.2627	0.2797	0.2772
0.7	0.3806	0.3814	0.3575	0.3807	0.3773
0.8	0.4972	0.4981	0.4670	0.4972	0.4928
0.9	0.6290	0.6304	0.5910	0.6293	0.6237
1	0.7768	0.7783	0.7299	0.7769	0.7428

Table 2. Splice loss values at a wavelength of 1550 nm.

Angular (°)	Splice loss (dB)				
	SMF 28	SMF 28e	SMF 28e+	SMF 28e+LL	SMF 28ULL
0.1	0.0073	0.0072	0.0067	0.0073	0.0072
0.2	0.0292	0.0290	0.0268	0.0292	0.0289
0.3	0.0657	0.0654	0.0605	0.0657	0.0651
0.4	0.1168	0.1163	0.1075	0.1168	0.1158
0.5	0.1825	0.1817	0.1680	0.1825	0.1810
0.6	0.2629	0.2617	0.2419	0.2629	0.2606
0.7	0.3578	0.3562	0.3293	0.3578	0.3547
0.8	0.4673	0.4652	0.4301	0.4674	0.4633
0.9	0.5914	0.5888	0.5443	0.5915	0.5864
1	0.7302	0.7269	0.6720	0.7302	0.7239

Simulation results, presented in Table 1 (1310 nm) and Table 2 (1550 nm), consistently demonstrate a substantial increase in splice loss with increasing angular misalignment across all five investigated SMF types. Results indicate that angular misalignment non-linearly and significantly increases splice loss [18], with a drastic rise in loss at larger angles (1°) [19]. A comparison between 1310nm and 1550nm wavelengths reveals very small and practically negligible differences in splice loss (±0.002dB) [20]. A key finding is the consistently lower splice loss observed at 1550 nm compared to 1310 nm across all misalignment levels, highlighting its superior robustness. The main conclusion is that splicing precision plays the most crucial role in minimizing splice loss [18], far more dominant than the choice of wavelength between 1310 nm and 1550 nm for this type of loss. Furthermore, SMF 28e+ consistently exhibited the lowest splice loss values among all variants, indicating its enhanced resilience to angular deviation. On the other hand, SMF 28e generally showed slightly higher losses. This universal sensitivity of all SMF types to angular misalignment underscores the critical importance of precise alignment during practical splicing operations to minimize signal degradation and ensure optimal optical system performance.

5. CONCLUSION

This paper confirms that angular misalignment is the dominant factor significantly increasing splice loss across all single-mode fiber (SMF) types. Key findings reveal SMF 28e+ consistently exhibits the lowest splice loss, with 1550 nm transmission generally outperforming 1310 nm in all conditions. This consistent sensitivity to angular misalignment, even in advanced SMF variants, underscores its critical impact on fusion splicing integrity. Therefore, minimizing angular misalignment is paramount for maintaining low splice loss and ensuring the long-term performance and reliability of optical communication systems. This requires strict adherence to precise splicing techniques and the utilization of high-precision alignment tools to preserve signal integrity across various SMF deployments.

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