IEEE Access
Multidisciplinary | Rapid Review | Open Access Journal

Received June 12, 2019, accepted June 30, 2019, date of publication July 8, 2019, date of current version August 7, 2019.

Digital Object Identifier 10.1109/ACCESS.2019.2927395

Modeling the Splice Loss of Single-Mode Optical Fibers Affected by Altitude

ZIRU CUI[1], (Student Member, IEEE), CHAOWEI YUAN[1], KEHANG XU[1,2], YONG SUN[1,3], (Member, IEEE), AND SHAN YIN[4]

[1]School of Information and Communication Engineering, Beijing University of Posts and Telecommunications, Beijing 100876, China
[2]Southwest Branch of State Grid Corporation of China, Chengdu 610041, China
[3]Beijing Key Laboratory of Network System Architecture and Convergence, Beijing University of Posts and Telecommunications, Beijing 100876, China
[4]State Key Laboratory of Information Photonics and Optical Communications, Beijing University of Posts and Telecommunications, Beijing 100876, China

Corresponding author: Chaowei Yuan (yuancw2000@bupt.edu.cn)

This work was supported in part by the National High Technology Research and Development Program of China under Grant 2014AA01A701 and Grant 2015AA01A705, and in part by the Science and Technology Project of State Grid Corporation of China [Key technology research and equipment development on high altitude Extra-High Voltage (EHV) long-chain power grid] under Grant SGLNDK00KJJS1700200.

ABSTRACT Splicing loss of optical fibers has always been the focus of attention in engineering. With the construction of communication networks in high altitude areas, more attention has been paid to the fusion of optical fibers in high altitude areas. A mathematical model of single-mode optical fibers splice loss affected by altitude is established in this paper. The model takes the splice loss caused by the mismatch in mode field diameters (MFD), angular misalignment and lateral misalignment into account, as well as the influence of atmospheric pressure on splicing angular misalignment. Fiber fusion experiments are carried out at different altitudes. The proposed model is validated by the experimental results and can be used as a reference to future research on the splice loss of single-mode fibers in plateau areas.

INDEX TERMS Ultra-low loss single-mode fibers, splice loss, optical fiber applications, high altitude areas.

I. INTRODUCTION

Single-mode optical fibers have been widely used in optical communication systems because of their good performance. Application area of Ultra-low Loss (ULL) single-mode optical fiber is spreading out to terrestrial networks due to its low loss, such as high altitude areas and depopulated zone [1]–[3]. Fusion splicing is a significant operation in the construction of fiber optic systems [4]. The splice loss of optical fibers has aroused a lot of interest in the past decades. The well-known loss analysis by Marcuse is a significant achievement of single-mode fibers splice [5]. Marcuse modeled the splice loss of fibers as a function of mismatch in mode field diameters (MFD), lateral misalignment and angular misalignment of the core. In the fusion loss model of optical fibers proposed by Das in [6], a certain pressure should be applied to the direction of the fiber axis to reduce the air gap before fibers fusion. Whereas the terrestrial network requires the applicability to various temperatures, altitudes and so on, and the splice losses show different values at different altitudes. Whereas both [5] and [6] established the model in a stable and unchangeable external environment, and the splice loss calculated by [5] or [6] is inconsistent with the actual splice loss at different altitudes, therefore these two models can not accurately reflect the splice loss in different altitude areas. Distribution of splice loss in single-mode optical fibers was studied in [7] and it can be used to estimate the splice loss of single-mode optical fibers, which indicates that the splice loss of single-mode optical fibers is still a meaningful research direction.

To the best of our knowledge, there has been no reported a statistical model for the splice loss of single-mode optical fibers in different altitude areas. We establish a mathematical model of splice loss in single-mode optical fibers affected by altitude in this work. The model takes the fusion loss caused by the mismatch in MFD, lateral misalignment and angular misalignment of the core into account, as well as the force variation of fiber butt-joint caused by the change of altitude and the influence of force variation on angular misalignment. Several experiments at different altitudes were set up to

The associate editor coordinating the review of this manuscript and approving it for publication was Sukhdev Roy.

validate the model, and then the model and experimental results are compared. The results illustrate that the model agrees more or less with the experimental data.

We expect that our proposed model will be beneficial to the following scenario. Single-mode optical fiber is widely used in every kind of network. Optical fiber fusion operation is indispensable to the construction of the network. The splice loss is an essential parameter to guarantee the regular operation of the network. When an optical fiber fusion operation was deployed, all the parameters of the fibers can be given by the optical fiber manufacturer and the environmental parameters can be obtained by test instruments. In this situation, the splice loss can be calculated by the proposed model, and the value could be a helpful reference at any altitude.

The paper is structured as follows. In Section 2, analysis by Marcuse on the splice loss of single-mode optical fiber is reviewed, and the effect of pressure between fibers on angular misalignment proposed by Das is reviewed. Thereby, a brief summary of their mathematical models is made and the force of fibers butt-joint before heating at different altitudes is analyzed. Then based on the Marcuse analysis and the Das analysis, a model of splice loss in single-mode optical fibers affected by altitude is established. In Section 3, the experimental equipment, experimental technique, setups and environmental parameters at different altitudes are discussed. Section 4 focuses on the verification of the proposed model by experimental results, and the proposed model, the Marcuse model, the Das model, and experimental results are compared. The main contents and conclusions of the work are given in Section 5.

II. MODELING THE SPLICE LOSS

In general, there are three cases in the fiber splicing process that affected the splice loss [5], i.e., splice loss caused by the mismatch in MFD is shown in Fig. 1(a), splice loss because of the lateral misalignment is shown in Fig. 1(b), and splice loss due to the angular misalignment is shown in Fig. 1(c).

ω_1, ω_2 are denoted as the mode field radii of two fibers, and d and θ are defined as the lateral misalignment and angular misalignment associated with a splice. Marcuse discussed the effect of the above three cases on the splice loss [5], the transmission of mismatch in MFD through the splice is modeled as

$$t(\omega) = \left(\frac{2\omega_1\omega_2}{\omega_1^2 + \omega_2^2}\right)^2. \tag{1}$$

The transmission of lateral misalignment through the splice is modeled as

$$t(d) = \exp\left[-\frac{2d^2}{(\omega_1^2 + \omega_2^2)}\right]. \tag{2}$$

The transmission of angular misalignment through the splice is modeled as

$$t(\theta) = \exp\left[-\frac{2(\pi n \omega_1 \omega_2 \theta)^2}{(\omega_1^2 + \omega_2^2)\lambda^2}\right]. \tag{3}$$

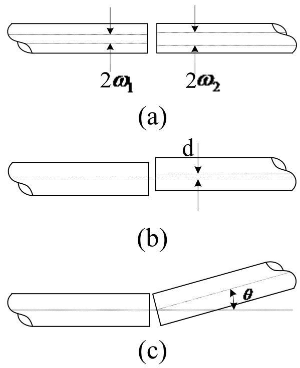

FIGURE 1. Types of splice loss: (a) mismatch in MFD, (b) lateral misalignment, and (c)angular misalignment.

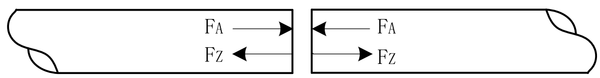

FIGURE 2. Schematic diagram of the force of the fiber fusion process.

where n is the index of refraction of the fiber cladding, and λ is the wavelength of light.

Splice loss in decibels is related to t by

$$Loss(\mathrm{dB}) = -10\log(t). \tag{4}$$

where the base 10 logarithm is taken.

Based on Marcuse analysis, a model of splice loss in single-mode optical fibers affected by altitude is proposed. As the first step in the fusion operation, the fibers are first aligned in the fusion splicer. Pressure F_A is applied to the fibers to reduce the air gap before heating. It is recognized that the air present in the air gap will exert a reverse force to the fibers butt-joint, that is, atmospheric pressure F_Z, as shown in Fig. 2. In an area where the altitude is 0, the standard atmospheric pressure intensity is expressed as P_0, and thus the force of the fibers butt-joint is given by $F_A - F_0 = F_A - P_0 \cdot \mathrm{s}$, s represents the cross-sectional area of the optical fiber cladding, because the atmospheric pressure not only acts on the core. Yet in high altitude areas, the air is thin and the atmospheric pressure F_Z in the air gap decreases, and the applied pressure F_A between the fibers is fixed, so the force of the fiber butt-joint is increased. The atmospheric pressure intensity at altitude Z is expressed as P_Z, and the force of the fiber butt-joint at altitude Z is given by $F_A - F_Z = F_A - P_Z \cdot \mathrm{s}$. In accordance with the above analysis, the force of the fiber butt-joint will increase in high altitude areas. The model by Das indicated that the force of the fiber butt-joint affects the angular misalignment of the fiber fusion [8]. Das spliced fibers in a plain area and ignored the effect of atmospheric pressure on the force of the fibers, the angular misalignment of fiber fusion with applied pressure F_A is expressed as [8]

$$\theta = \theta_0 \exp(K_A F_A)^m. \tag{5}$$

where θ_0 is the initial tilted angle, K_A and m are constants depending on the end face condition of the fibers, i.e. contaminants on the cutting end, the burred edges and the inclination

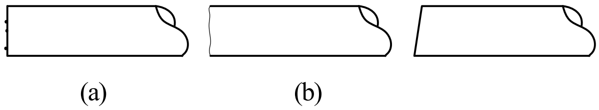

FIGURE 3. Schematic diagram of the end condition of the fibers: (a) some contaminants, (b) the burred edges, and (c) end tilt.

of fiber end face caused by cutting, as shown in Fig. 3. As mentioned above, the effect of atmospheric pressure on the force of the fibers butt-joint is considered. With the altitude increases, the force of the fiber butt-joint increases, the force difference in the fiber butt-joint between altitude Z and 0 is (F_A-F_Z)-(F_A-F_0), i.e., $(P_0 - P_Z) \cdot s$. Hence, the angular misalignment of the fiber fusion at altitude Z is given by

$$\theta_Z = \theta_0 \exp[K_A(F_A + (P_0 - P_Z) \cdot s)]^m. \tag{6}$$

The atmospheric pressure intensity is an important parameter in equation (6). With the altitude increases, the atmospheric pressure gradually decreases. On the basis of the ideal atmospheric equation (7) and atmospheric static equation (8) in [9]

$$P = \rho RT. \tag{7}$$

$$\partial P/\partial Z = -\rho g. \tag{8}$$

It can be derived a general pressure-altitude equation

$$-(g/TR)\,\partial Z = \partial P/P. \tag{9}$$

where g is the acceleration of gravity, T is the Kelvin temperature, R is the gas constant of dry air, Z is the altitude. The integration of the equation (9) is

$$\ln(P_Z/P_0) = \int_{Z_0}^{Z} -(g/TR)\partial Z. \tag{10}$$

Then, the atmospheric pressure intensity P_Z at altitude Z is

$$P_Z = P_0 \cdot e^{\int_{Z_0}^{Z} -(g/TR)\partial Z} = P_0 \cdot e^{-(g/TR)(Z-Z_0)}. \tag{11}$$

Combining equations (3), (4), (6) and (11), the angular misalignment loss of the fiber fusion affected by altitude can be expressed as

$$L(\theta_Z) = -10\log\{\exp[-2(\pi n\omega_1\omega_2\theta_0 \exp(K_A(F_A + (P_0 - P_0 \cdot e^{-(g/TR)(Z-Z_0)}) \cdot s))^m)^2/((\omega_1^2 + \omega_2^2)\lambda^2)]\}. \tag{12}$$

Thus fusion loss is given by

$$Loss(\text{dB}) = f(\omega, d, \theta_Z). \tag{13}$$

Substituting (1), (2), (4), (12) into (13) to obtain the total loss of fibers fusion at altitude Z

$$Loss(\text{dB}) = L(\omega) + L(d) + L(\theta_Z). \tag{14}$$

Many errors coexist in the splicing process, such as the errors caused by the human operation and experimental equipment, and the minor error caused by different manufacture batches of optical fibers. These errors will affect the final splice loss. So it is necessary to consider these errors in the analysis of the actual splice loss and the theoretical result. Therefore, the relationship between actual measured splice loss and the theoretical result can be expressed as

$$L_{tot} = Loss(\text{dB}) \pm \sigma. \tag{15}$$

TABLE 1. Information of the test points in experiment 1.

Environmental Information	Test Point1	Test Point2	Test Point3
Temperature(℃)	24	24	18
Humidity(%RH)	50	50	50
Altitude(m)	53	2980	5200

III. EXPERIMENTAL

A. EXPERIMENT 1

The experiment relies on the central Tibet network engineering in China. Three test points in different altitudes are selected in experiment 1 to carry out the research. The environmental information about the three test points as summarized in Table 1. Two ULL single-mode optical fibers of the same type as those used in the project are selected for the fusion experiments, and the length of each fiber is 500 meters. Sumitomo 81c fusion splicer is selected, which is the same as the fusion splicer used in engineering, the fusion mode is SM G652 Std., and other splicing parameters remain at their default values. Fiber end faces are prepared by cleaving using a wire stripper Sumitomo FC-6S, so the end conditions of optical fibers after each cutting are the same. Then the splice loss at 1550nm is measured by an Optical Time Domain Reflectometer (OTDR) after splicing, and the OTDR adopts a bi-directional approach. The fusion experiment is repeated 10 times for each test point. To improve the spatial resolution of the OTDR and obtain accurate measurement results, appropriate parameters of OTDR should be set before the test. An effective way to improve spatial resolution is to reduce the optical pulse duration. According to the length and working wavelength of experimental fibers, the measurement range, pulse duration and average time of OTDR are set as suitable values to get high measuring accuracy. In the progress of measurement, the location of the fusion point in OTDR traces is an important segment. There will show either a step-down or a step-up on the OTDR trace with respect to the splice loss. The OTDR measurement cursor was located on both sides of the step and close to the step. The result of the measurement is the splice loss. A bi-directional approach was adopted, so the measurement cursor of OTDR must be adjusted in each direction during the measurement.

Fusion operation is a method of fusing the end of optical fibers by using the heat generated by discharge. For the reason that the optimal discharge conditions will vary with the external conditions (such as altitude, air pressure, temperature, etc.), before the fiber fusion operation, it is necessary to

TABLE 2. Environmental information of the test points in experiment 2.

Environmental Parameters	Test Point1	Test Point2	Test Point3	Test Point4
Temperature(℃)	18	21	24	27
Humidity(%RH)	50	50	50	50
Altitude(m)	53	53	53	53

perform discharge calibration on the fusion splicer. Discharge calibration is a process of transforming discharge conditions according to the fusing length of optical fibers. After the discharge calibration is completed, the fusing length of optical fibers should be the same. The optical fiber feed of the fusion splicer used in this experiment is fixed, the fusing length of optical fibers is the same, and the same fusion mode is adopted, so the fusion time and fiber feed rate are the same for each fusion. Hence, we get the same fusing conditions after every discharge calibration. The operation of discharge calibration on fusion splicer before fusion is the precondition to ensure the same fusing conditions.

B. EXPERIMENT 2

The effect of altitude on the fusion loss is discussed in this work. Three environmental parameters in experiment 1 jointly affect fusion performance. So it is necessary to exclude the effect of temperature and humidity variety on the splice loss. Fusion experiments 2 under the same altitude, same humidity, and different temperatures are carried out to study the variation of fibers fusion loss. Experiment 2 adopts the same ULL single-mode optical fibers, wire stripper, fusion splicer, the fusion mode and other fusion parameters as experiment 1. The range of temperature in experiment 2 should be larger than that in experiment 1. The experiment is repeated 10 times at each temperature, and then the average of the results is calculated. The environmental parameters in experiment 2 are listed in Table 2, and the average values of the experimental results of experiment 2 are listed in Table 3. The results show that the variation of the splice loss in the range of 18-27°C is extremely little and not more than 10^{-3}. Therefore, the influence of temperature variation on the splice loss in experiment 1 can be neglected. And the humidity values of three test points in experiment 1 are the same, so it can be considered that the only factor affecting the splice loss in experiment 1 is the altitude.

For errors, we quantified the operation error based on the statistical experiments. The errors of three experimental points in experiment 1 are $\sigma_1 = 0.0026$, $\sigma_2 = 0.0049$, $\sigma_3 = 0.0089$, respectively.

IV. RESULTS AND DISCUSSION

The parameters of the two ULL single-mode optical fibers used in the experiment are listed in Table 4. The core-cladding concentricity specified by the optical fiber manufacturer is $d \leq 0.5\mu$m [4], and the measured core-cladding concentricity of two optical fibers used in the experiment is 0.085μ m and 0.01636μm, respectively, so the offset d is set to

TABLE 3. Splice loss of the test points in experiment 2.

Test Point	Test Point1	Test Point2	Test Point3	Test Point4
Splice loss(dB)	0.0187	0.0191	0.0181	0.0188

TABLE 4. Fiber parameters @1550nm.

Fiber	Core Diam. (μm)	Clad Diam. (μm)	MFD (μm)	Concent. (μm)
1#	8.63	125.12	10.44	0.085
2#	8.36	125.11	10.26	0.1636

$d = 0.085 + 0.1636 = 0.2486\mu$m. (It is recognized that all of the fusion splicers attempt to align the core to achieve a lower splice loss, and the worst offset value is used, nevertheless, it is a reasonable value in this work). In the experiment, the limitations of the cleaver and the core angle are 2° and 1°, and $\theta_0 = 2$ is used as the initial angular misalignment. The cladding refractive index of ULL single-mode optical fiber at 1550nm is $n = 1.462$. For all kinds of optical fibers, whether ULL single-mode optical fiber or traditional single-mode optical fiber, the end face conditions of the fibers depending on the cutting conditions, and the cutting conditions in this work are the same as what has been previously discussed in [8], hence, K_A and m in equations (5), (6) and (12) are the same as that in [8], that is, $K_A = 0.022$, $m = 2$. In equation(9), $g = 9.8$N/kg, T is the Kelvin temperature, the relationship between T and Celsius temperature t is $T = 273.15 + t$. Due to the temperatures of the three test points in experiment 1 are different, we take t as its average here, i.e., $t = 22$°C, and $R = 287.05\ \mathrm{J \cdot kg^{-1} \cdot K^{-1}}$, $P_0 = 101.3$kPa.

In equation (6), the value of F_A should be known, and F_A is the pressure applied when the minimum splice loss is obtained. On the premise of the values set above, the air gap loss was calculated by using equation (24) in [8], the angular misalignment loss was calculated by using equation (3) and (4), the offset misalignment loss was calculated by using equation (2) and (4), the MFD loss was calculated by using equation (1) and (4), the theoretical values of individual loss and their summation against applied pressure F_A are shown in Fig. 4. It is conspicuous from Fig. 4, the minimum splice loss is achieved when the applied pressure $F_A = 0.21$N. The unit of F_A in [8] is gm., whereas the unit of F_A we used in equation (6) is Newton, so the unit conversion is required in the calculation progress.

The theoretical curve of angular misalignment of fiber fusion can be calculated by using (6) and the F_A above, the result versus altitude is shown in Fig. 5. As can be seen from Fig. 5, the angular misalignment of fiber fusion increases with the altitude. When F_A is a fixed value, the increased altitude results in the angle increase, which contributes to the splice loss.

Fig. 6 shows the theoretical values of individual loss and their summation versus altitude. It can be concluded that the

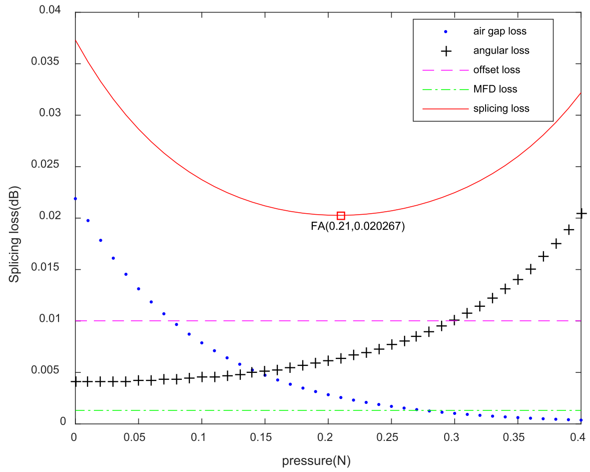

FIGURE 4. Theoretical values of air gap loss (blue circle dots), angular misalignment loss (black plus sign dots), offset misalignment loss (magenta dashed line), MFD loss (green dash-dotted line) and splice loss (red solid line) against applied pressure.

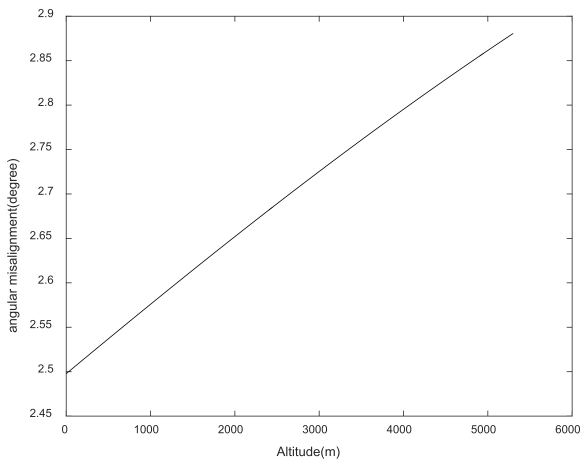

FIGURE 5. Angular misalignment against altitude.

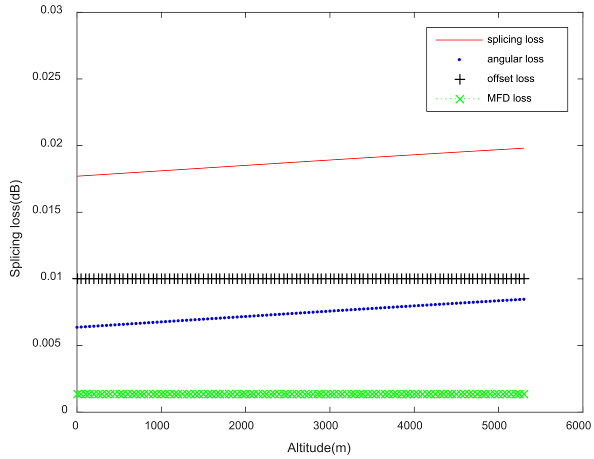

FIGURE 6. Theoretical values of angular misalignment loss (blue circle dots), offset misalignment loss (black plus sign dots), MFD loss (green cross line) and splice loss (red solid line) against altitude.

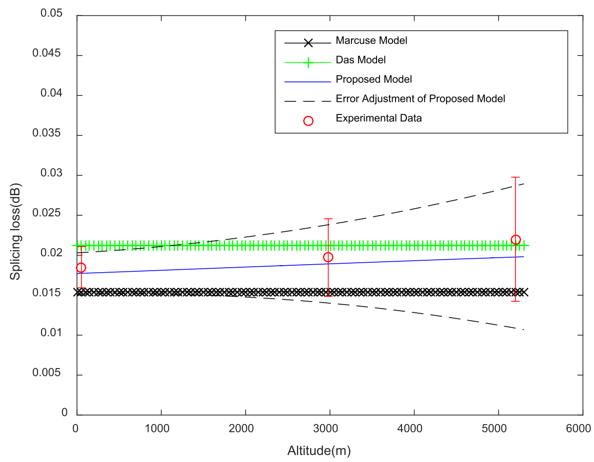

FIGURE 7. Contrast diagram of splice loss between our proposed model (blue solid line), Marcuse model (black cross line), Das model (green plus sign line), experimental data (red circles) and the error bars of experimental data (red vertical lines). The two black dashed lines represent our proposed model adjusted by error, i.e., *Loss* $\pm\sigma$.

loss caused by the mismatch in MFD is extremely insignificant because of the similar MFD of two ULL fibers, it is logical that the splice loss will depend mainly on the losses due to angular misalignment and offset misalignment. It can also be found that the losses caused by offset misalignment and mismatch in MFD are fixed, whereas the angular misalignment loss increases with the increase of altitude, and therefore the total splice loss increases with the increase of altitude.

To verify the accuracy of the proposed model, the contrast between the proposed model, the Marcuse model, the Das model, and experimental data are made, and the results are shown in Fig. 7. It can be seen from Fig. 7 that the splice loss calculated by the Marcuse model or the Das model is fixed and does not vary with the altitude, which is inconsistent with the tendency of experimental results. Whereas our proposed model agrees more or less with the experimental results, and the splice loss calculated by the proposed model increases with the increase of altitude. The error between the proposed model and experimental results is significantly lower than the error between the Marcuse model, the Das model, and experimental results. It can also be seen in Fig. 7 that the error of the experimental data is very low in the plain area and the error increases as the altitude increases. This phenomenon can be explained as the fusion splicer in high altitude areas that has unstable performance and larger error than in plain areas, even so, the splice loss still meets the engineering requirements.

A fixed lateral offset d, and angular misalignment θ are considered in the above paragraphs. Nevertheless, the lateral misalignment and angular misalignment of each splice are random in the actual fusion operation, and it is required to consider this nature in the analysis. Several different groups of values are used to calculate the splice loss, and the comparisons between the calculated results and experimental data are shown in Fig. 8. It can be seen from Fig. 8, different offset and angle will cause different splice loss, whereas all the splice losses calculated by the proposed model agree more or less

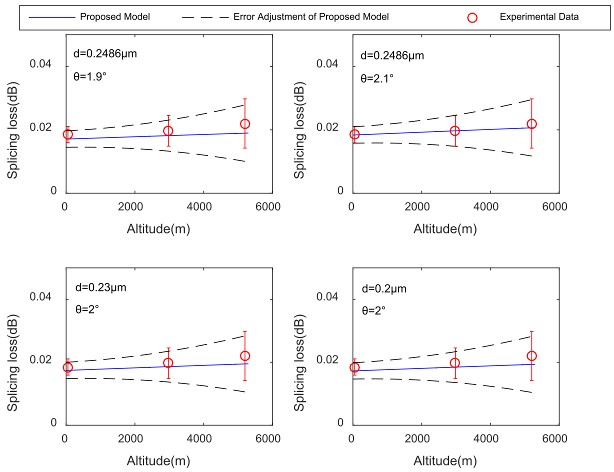

FIGURE 8. Contrast schematic diagram between splice loss of the proposed model under different offset and angle (blue solid line) and experimental data (red circles).

with the experimental results, and the proposed model has been verified further.

V. CONCLUSION

In this work, a model of splice loss in single-mode optical fibers affected by altitude is proposed. The model takes the splice loss caused by the mismatch in MFD, lateral misalignment and angular misalignment of the core into account, as well as the force variation of fiber butt-joint caused by the change of altitude and the influence of force variation on angular misalignment. The force of the fiber butt-joint increases as the altitude increases, then the angular misalignment of fiber fusion will be larger, therefore the splice loss due to angular misalignment increases. The fusion experiments of ULL single-mode optical fibers are carried out by traditional commercial fusion splicer at three altitudes. The proposed model was demonstrated by the experimental result, and the error between the proposed model and experimental results is significantly lower than the error between the Marcuse model, the Das model, and experimental results. This means that our model can be used as a reference to future research on the splice loss of single-mode optical fibers in Plateau areas.

In the experiment, the force of fiber butt-joint by fusion splicer F_A is fixed due to the limitation of fusion splicer, whereas the splicing loss in different altitudes can be optimized by adjusting the applied pressure of fusion splicer in the future. The splicer operator can change the F_A in any altitude to guarantee that the force of the fibers butt-joint remains unchanged, and this is another way to reduce the splice loss in high altitude areas, yet the fusion splicer needs to have a custom function.

We expect that the proposed model will be useful in the following scenario. In this scenario, two single-mode optical fibers will be spliced, and the optical wavelength, the allowable maximum angular misalignment, and the allowable maximum lateral offset have been known. In addition, the types of fiber are known, so the mode-field diameter and the cladding refractive index can be known. The altitude of the location of fusion operation also can be known. With these parameters, the splice loss in this location will be obtained by calculation, and the calculated value could be used as a guide to splice operation.

APPENDIX

LIST OF SYMBOLS

Symbol	Meaning of Symbol	Units
ω_1, ω_2	Mode field radius of fiber1, fiber2	μm
d	Lateral misalignment of fiber fusion	μm
n	The index of refraction of the fiber cladding	-
$\theta, \theta_0, \theta_Z$	Angular misalignment, initial tilt angle, angular misalignment at altitude Z	degree
λ	The wavelength of light	-
F_A, F_Z	The force of the fiber butt-joint by fusion splicer, the force of the fiber butt-joint by atmospheric pressure	N
K_A	A constant depends on the end condition of the fibers	-
m	A constant depends on the end condition of the fibers	-
P_0, P_Z	The atmospheric pressure intensity at altitude 0, the atmospheric pressure intensity at altitude Z	kPa
s	The cross-sectional area of the optical fiber	m^2
g	The acceleration of gravity	N/kg
T	Kelvin temperature	K
R	The gas constant of dry air	$J \cdot kg^{-1} \cdot K^{-1}$
Z	Altitude	m
$\sigma, \sigma_1, \sigma_2, \sigma_3$	Error, error at test point 1, error at test point 2, error at test point 3	dB

ACKNOWLEDGMENT

The authors would like to thank the editor and the reviewers for their reviews and suggestions to help us improve the quality of this paper.

REFERENCES

[1] Y. Tamura, H. Sakuma, Y. Yamamoto, and T. Hasegawa, "Ultra-low loss silica core fiber for long haul transmission," in *Proc. Conf. Lasers Electro-Opt., Opt. Soc. Amer. Tech. Dig.*, 2018, Paper SF2K.3.

[2] B. Zhu, P. I. Borel, T. Geisler, R. Jensen, L. Leng, X. Jiang, D. W. Peckham, R. L. Lingle, D. Vaidya, M. F. Yan, P. W. Wisk, and D. J. DiGiovanni, "800Gb/s (8×128Gb/s) unrepeatered transmission over 515-km large-area ultra-low-loss fiber using 2nd-order Raman pumping," *Opt. Exp.*, vol. 24, no. 22, pp. 25291–25297, Oct. 2016.

[3] D.-I. Chang, P. Perrier, H. Fevrier, T. J. Xia, D. L. Peterson, G. A. Wellbrock, S. Ten, C. Towery, and G. Mills, "Unrepeatered 100G transmission over 520.6 km of G.652 fiber and 556.7 km of G.654 fiber with commercial Raman DWDM system and enhanced ROPA," *J. Lightw. Technol.*, vol. 33, no. 3, pp. 631–638, Feb. 1, 2015.

[4] A. D. Yablon, *Optical Fiber Fusion Splicing*. Berlin, Germany: Springer-Verlag, 2005.

[5] D. Marcuse, "Loss analysis of single-mode fiber splices," *Bell Syst. Tech. J.*, vol. 56, no. 5, pp. 703–718, May/Jun. 1977.

[6] A. K. Das and S. Bhattacharyya, "Optimum conditions for fusion splicing of optical fiber," *Proc. IEEE*, vol. 72, no. 7, pp. 983–984, Jul. 1984.

[7] J. M. Nichols, J. V. Michalowicz, and F. Bucholtz, "Distribution of splice loss in single mode optical fiber," *Appl. Opt.*, vol. 57, no. 5, pp. 1140–1150, Feb. 2018.

[8] A. Das and S. Bhattacharyya, "Low-loss fusion splices of optical fibers," *J. Lightw. Technol.*, vol. 3, no. 1, pp. 83–92, Feb. 1985.

[9] Z. Jiao, J. Hu, and X. Gong, "Research of altitude measurement method based on INS and pressure sensor," in *Proc. IEEE 2nd Inf. Technol., Netw., Electron. Autom. Control Conf. (ITNEC)*, Chengdu, China, Dec. 2017, pp. 1684–1687.

ZIRU CUI received the B.E. degree in electronic information engineering from the Liren College, Yanshan University, Qinhuangdao, China, in 2014, and the M.E. degree in electronic and communication engineering from the Kunming University of Science and Technology, Kunming, China, in 2017. She is currently pursuing the Ph.D. degree with the School of Information and Communication Engineering, Beijing University of Posts and Telecommunications. Her research interests mainly include optical fiber fusion, ultra-low loss optical fiber, fiber fusion loss, and reliability of optical fiber fusion.

CHAOWEI YUAN received the Ph.D. degree from Xi'an Jiaotong University, Xi'an, China, in 1994. He is currently a Professor with the School of Information and Communication Engineering, Beijing University of Posts and Telecommunications. His research interests mainly include wireless communication systems, new techniques in 5G systems, channel estimation, and symbol detection.

KEHANG XU was born in Renshou County, Leshan, Sichuan, China, in 1982. He received the B.S. degree in telecommunication engineering from Southwest Jiaotong University, Chengdu, Sichuan, China, in 2005, and the M.S. degree in telecommunication engineering from Chongqing University, Chongqing, China, in 2014. He is currently pursuing the Ph.D. degree with the School of Information and Communication Engineering, Beijing University of Posts and Telecommunications.

From 2005 to 2015, he was with State Grid Sichuan Electric Power. Since 2015, he has been with Southwest Branch of State Grid Corporation. He has been an Expert of working group in Electric Power Communication Standards Committee International Association of China, since 2017. He is the author of two industry standards, more than ten articles, and more than ten inventions. His research interests mainly include optical fiber communication, fiber fusion loss, reliability of optical fiber fusion, and optical networks.

YONG SUN (M'12) received the Ph.D. degree from the Beiijng University of Posts Telecommunications, Beijing, China, in 2008, where he is currently a Lecturer with the School of Information and Communication Engineering. His current research interests include heterogeneous networks, wireless resource allocation, and network management.

SHAN YIN received the Ph.D. degree in communication engineering from the Beijing University of Posts and Telecommunications, in 2014, where she is currently an Associate Professor with the State Key Laboratory of Information Photonics and Optical Communications. Her research interests include optical networks, optical networks design, and survivability of optical networks.