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Single-Mode Fiber Design for Long Haul Transmission

LUC JEUNHOMME

Abstract—**By using simple yet accurate approximations for the propagation characteristics of a single-mode optical fiber, we obtain a simple model for the total loss and chromatic dispersion of single-mode fiber transmission lines as a function of the operating conditions such as splice offset, microbending loss, bends, etc. This model is then applied to typical cases of terrestrial and submarine systems and we obtain single-mode fiber designs which are stable with respect to slight operating condition changes for both 1.3 and 1.55 μm wavelengths. It appears that the same fiber can be used at 1.3 μm for both terrestrial and submarine systems, and even for 1.55 μm terrestrial systems if monochromatic sources become available at this wavelength. A general comparison between the two wavelengths is carried out and shows under which conditions the 1.55 μm wavelength is of practical interest. It is emphasized that the availability of monochromatic sources at 1.55 μm would make a major breakthrough for the repeater spacing.**

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I. Introduction

The achievement of very low loss single-mode optical fibers and the improvements in the knowledge of light propagation inside these fibers make them very attractive for long distance transmission in the telecommunication network. This means that system designers begin to be practically interested in implementing single-mode fiber based systems. At this point several questions are raised among which are the following:

1) For a given application and given operating conditions, what are the optimum parameters for the single-mode fiber structure (namely core radius and index difference). This question obviously stems from the fact that many transmission characteristics of the fiber depend on these basic parameters in a complicated and apparently opposite way (e.g., microbending losses and splicing losses).

2) Between the two well-known low attenuation windows

(1.3 and 1.55 μm center wavelengths) what are the respective advantages and drawbacks, and in which case or under which conditions is it better to choose one or the other.

This paper describes a general optimization procedure of the basic parameters of the single-mode fiber with respect to given operating conditions, and the possibilities of this procedure are illustrated by typical examples which, at least partially, answer the above questions.

Section II is devoted to getting simple models for the intrinsic fiber loss, microbending loss, splicing loss, curvature loss, and chromatic dispersion from existing models, which usually require the use of large scale computers. We start here from these existing models and find analytical approximations which can be worked out on a scientific pocket calculator, thus making the optimization procedure much more easy to handle.

Section III describes the optimization procedure itself and shows some results for given operating conditions, which are then discussed with respect to the questions asked above. Section IV draws some general conclusions based on the typical results shown above.

II. Propagation Models

We are concerned here with finding simple yet accurate models for the various transmission characteristics of the single-mode optical fibers such as intrinsic fiber loss, microbending loss, splicing loss, curvature loss, and chromatic dispersion.

For a step-index single-mode fiber, the structure is entirely described by any two parameters such as the core radius a, the core-cladding index difference Δn, the normalized cutoff frequency V, or the cutoff wavelength of the LP_{11} mode λ_c. Well-known relationships hold between the parameters

$$V = 2\pi \frac{a}{\lambda} (2n_2 \Delta n)^{1/2} \tag{1}$$

$$V = 2.4 \frac{\lambda_c}{\lambda} \tag{2}$$

where λ is the light wavelength in vacuum and n_2 is the cladding index of refraction which will be taken as 1.45 (silica refractive index) in the following.

For the model to be developed here, we chose to use Δn and λ_c as the set of parameters describing the single-mode fiber. Since generally, single-mode fibers do not exhibit a perfect step-index profile in the core, the parameters used here should be understood as those characterizing the step-index equivalent to the actual refractive index profile (e.g., [1]).

A. Intrinsic Fiber Loss

The intrinsic fiber loss α_i is mainly composed, in the wavelength range of interest here, of residual IR and (OH^-) ions absorption and of Rayleigh scattering. The former is almost independent of the dopant concentration and thus, of the index difference Δn, provided proper manufacturing conditions are used [2]. We assume a value of 0.05 dB/km for the residual absorption, independent of wavelength as IR absorption is more important at 1.55 μm than at 1.3 μm, whereas (OH^-) ions absorption is less [3].

For the Rayleigh scattering, we used measurements carried out at 0.9 μm as a function of Ge concentration in multimode fibers [4] to draw a linear relationship as a function of Δn, and thus, we get the total intrinsic loss as

$$\alpha_i = 0.05 + (0.75 + 66\,\Delta n)\,\lambda^{-4} \tag{3}$$

α_i in dB/km, λ in μm.

This relationship agrees well with many published results on low loss single-mode fibers (e.g., [3], [5]).

B. Microbending Loss

For evaluating microbending losses, we use the results of [6] and more specifically, (48) of [6], which compares the microbending induced loss in single-mode and multimode fibers. However, for the purpose of being consistent with the calculations concerning splicing losses, we use the Gaussian approximation definition of the mode radius w_o to e^{-2} in intensity [7]. After correcting by a factor $2^{1/2}$, accounting for the change from e^{-2} to e^{-1} intensity between [7] and [6], there still remains a small difference between the two definitions. However, it has been shown [8] that the difference is quite small and should not impair the present results. Considering as a reference the microbending induced loss α_{MM} on a multimode optical fiber with a 50 μm core diameter and a 0.2 NA we obtain for the single-mode fiber

$$\alpha_{SM} = 2 \times 10^{-4}\, w_o^6\, \lambda^{-4}\, \alpha_{MM} \tag{4}$$

where w_o and λ should be expressed in μm and both the multimode and the single-mode fiber should have the same outside diameter.

For w_o, we obtain from [7] by using (1) and (2)

$$w_o = \lambda_c (\Delta n)^{-1/2} \left[0.145 + 0.097 \left(\frac{\lambda}{\lambda_c}\right)^{3/2} + 0.0033 \left(\frac{\lambda}{\lambda_c}\right)^6\right] \tag{5}$$

$n_2 = 1.45$ has been used in (1).

Practically, α_{MM} should be understood as including drawing induced waveguide defects, cabling induced microbends, as well as effects of abrupt changes of curvature [9].

C. Splicing Loss

Splicing losses are due to structural parameter fluctuations from fiber to fiber, lateral offsets between the cores, and tilts between the fiber axes. Using the results of [7], we observe that structural parameter fluctuations induce a loss of 0.05 dB for $\delta w_o / w_o = 11$ percent. Using (1), (2), and (5) and designating the terms within brackets in (5) as $f(\lambda/\lambda_c)$, we obtain

$$\frac{\delta w_o}{w_o} = \left[1 - \frac{\lambda}{\lambda_c} \frac{f'(\lambda/\lambda_c)}{f(\lambda/\lambda_c)}\right] \frac{\delta a}{a} - \frac{1}{2} \frac{\lambda}{\lambda_c} \frac{f'(\lambda/\lambda_c)}{f(\lambda/\lambda_c)} \frac{\delta(\Delta n)}{\Delta n} \tag{6}$$

where $f'(x)$ is the derivative of $f(x)$ with respect to x.

As will be seen in Section III, the interesting results all lie within the range $1.1 \leqslant \lambda/\lambda_c \leqslant 1.6$ which leads to

$$\left|\frac{\delta a}{a}\right| \leqslant +5 \text{ percent and } \left|\frac{\delta(\Delta n)}{\Delta n}\right| \leqslant 10 \text{ percent} \Rightarrow \frac{\delta w_o}{w_o} \leqslant 11 \text{ percent.} \tag{7}$$

We can thus consider that $|\delta a/a| \leqslant 5$ percent and $|\delta(\Delta n)/$

$\Delta n| \leqslant 10$ percent are a (reasonable) tolerance which ensure a splicing loss due to structural parameter fluctuations of less than 0.05 dB. We will thus fix this loss component to 0.05 dB in the following. Again, using the results of [7] we can then write the total splicing loss with a lateral offset d and an axes tilt θ(in rd) as

$$\alpha_S \approx 0.05 + 4.34 \left[\left(\frac{d}{w_o}\right)^2 + \left(\frac{\pi n_2 w_o}{\lambda} \theta\right)^2\right] \text{ dB.} \tag{8}$$

Practically, the transmission line is composed of single-mode fiber cable pieces spliced together. We can assume that there is a mean distance between successive splices, called L_S, and obtain thus an equivalent distributed splicing loss

$$\alpha_{SD} = \frac{\alpha_s}{L_s} \text{ dB/km.} \tag{9}$$

D. Curvature Loss

We treat here only the loss caused by constant curvature, as the loss due to abrupt changes of curvature can be treated as in Section II-D [9]. From [9], we get the constant curvature loss as

$$\alpha_c = CR^{-1/2} \exp - DR \tag{10}$$

where R is the radius of curvature, and D and C are related to the guide parameters

$$D = \frac{4 \Delta n W^3}{3 a V^2 n_2} \tag{11}$$

$$C = \frac{1}{2}\left(\frac{\pi}{aW^3}\right)^{1/2} \left[\frac{U}{VK_1(W)}\right]^2 \tag{12}$$

where U and W are the usual transverse propagation constants in the core and in the cladding, respectively.

Using (1) and (2) and the best known approximation for W [10], [11], we get for DR

$$DR = 7.1 \times 10^5 \frac{R}{\lambda} (\Delta n)^{3/2} \left[2.743 - 0.996 \frac{\lambda}{\lambda_c}\right]^3 \tag{13}$$

with R in m and λ in μm.

This approximation gives an accuracy of better than 3 percent for $0.8 \leqslant \lambda/\lambda_c \leqslant 2$. For C, a detailed study of the behavior of the exact function $W^{-3/2} [U/VK_1(W)]^2$ shows that it can be approximated to within 10 percent by $3.7(\lambda_c/\lambda)^2$ for λ/λ_c = 1-2. Thus,

$$CR^{-1/2} = 3.0 \times 10^7 (\Delta n)^{1/4} (\lambda R)^{-1/2} \left(\frac{\lambda_c}{\lambda}\right)^{3/2} \text{ dB/km} \tag{14}$$

with R in m and λ in μm.

E. Chromatic Dispersion

Starting from [12]-[14], it is easy to show that the total chromatic dispersion $\mathcal{C}$ = derivative of the group delay with respect to wavelength can be written as

$$\mathcal{C} = M_2 \left(1 + \frac{\Delta n}{n_2} \frac{d(VB)}{dV}\right) - \frac{\Delta n}{c\lambda} \left(V \frac{d^2(VB)}{dV^2} - P \frac{d(VB)}{dV}\right) \tag{15}$$

where $M_2(\lambda)$ is the material dispersion coefficient of silica, B is the normalized propagation constant [12], c is the light velocity in vacuum, and P is the profile dispersion parameter [13]. The only approximations in [15] are that it is to first order in Δn and second, that the group index of silica has been taken equal to its refractive index in the second term of the right-hand side after derivation of the exact formula (namely, $N_2 \Delta n/n_2$ has been replaced by Δn, which gives an error of less than 2 percent on this very small term [14]).

Practically, we have M_2 (1.3 μm) = 2.6 ps/nm · km and M_2 (1.55 μm) = 22 ps/nm · km[14]; P(1.3 μm) = 0.06 and P(1.55 μm) = 0.1 for Germanium doped fibers [13]. Again, there exist analytical formulas for $d(VB)/dV$ and $Vd^2(VB)/dV^2$ [15], but they cannot be handled with a pocket calculator.

For $d(VB)/dV$, we start from the approximation given in [10] and obtain

$$\frac{d(VB)}{dV} = 1.306 - 0.172 \left(\frac{\lambda}{\lambda_c}\right)^2. \tag{16}$$

This approximation gives an accuracy better than 3 percent from λ/λ_c = 1-1.8 [11].

Now there is no satisfactory approximation for $Vd^2(VB)/dV^2$ [11], but empirically, we get

$$V \frac{d^2(VB)}{dV^2} \approx 0.08 + 0.549 \left(2{,}834 - 2.4 \frac{\lambda_c}{\lambda}\right)^2. \tag{17}$$

This approximation gives an accuracy better than 5 percent from λ/λ_c = 1-1.8.

III. Optimization Procedure and Results

In the preceding section, we have established all the formulas which are useful to optimize the basic parameters λ_c and Δn of the single-mode fiber for a given application. The parameters characterizing the application which are needed are the operating wavelength λ, the drawing, cabling, and curvature changes induced loss α_{MM} in a multimode fiber (core diameter 50 μm, NA = 0.2), the typical offset d and tilt θ at splices, the mean distance between splices L_s, and the curvatures encountered by the fiber once it is laid in place.

A. Optimization Procedure

Starting with these parameters and the formulas of Section II, we compute the total loss α_T in dB/km for the fiber laid in place as a function of λ/λ_c and Δn and draw the corresponding surface. This surface exhibits an absolute minimum $\alpha_{T\min}$ for a given set of λ_c and Δn values, which are thus the optimum basic parameters of the fiber for this application. However, optimizing a fiber for only one set of application parameters would lead to dangerous conclusions because of the uncertainty on these application parameters, and may also be expensive in terms of the variety of products to be manufactured.

In other words, we try slightly different application parameters and find a common choice to all these cases and when possible, a common choice to different wavelengths. This is done by considering not only the absolute minimum for each case, but by accepting all the parameters λ_c and Δn which lead to a loss α_T exceeding $\alpha_{T\min}$ by less than 10 percent. We saw in Section II-C that $|\delta a/a| < 5$ percent and $(\delta(\Delta n)/\Delta n) <$

10 percent seem to be reasonable and acceptable tolerances for the fiber structural parameters. From (1) and (2) we get

$$\frac{\delta(\lambda/\lambda_c)}{\lambda/\lambda_c} = -\frac{\delta a}{a} - \frac{1}{2}\frac{\delta(\Delta n)}{\Delta n}. \tag{18}$$

This defines a "certainty surface" around a nominal point $(\lambda/\lambda_c, \Delta n)$, which is shown in Fig. 1.

Finally, by imposing that the fiber remains single-mode and that the total loss does not exceed the absolute minimum loss by more than 10 percent in all the global certainty surface, we obtain for each set of application parameters a usable surface which includes all the acceptable nominal values of λ_c and Δn. The optimum choice is then defined as the common point (s) between several usable surfaces corresponding to different cases. When possible, we then consider the value of the chromatic dispersion for defining the correct choice.

Another approach can be to require the chromatic dispersion to be zero and then find the lowest loss among the possible points. This can be used especially for 1.55 μm which will be treated separately (see Section III-D).

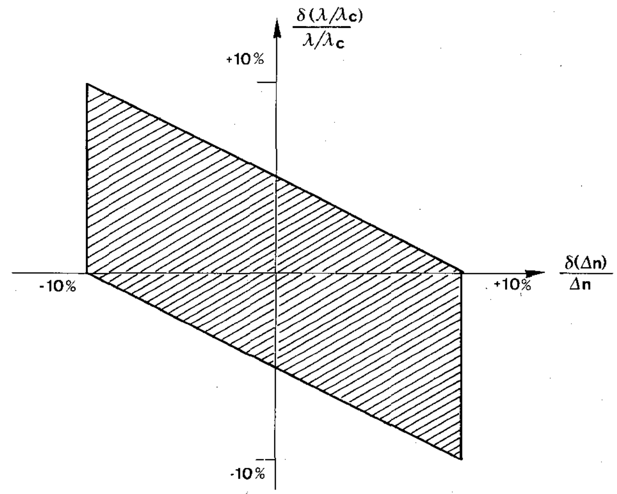

Fig. 1. "Certainty surface" for λ/λ_c and Δn around a given nominal point.

B. Terrestrial Systems

For terrestrial systems, we considered the following situations:

1) $\lambda = 1.3$ and 1.55 μm.

2) $\alpha_{MM} = 0.15$ dB/km which seems to be a reasonable and well-established figure for state of the art drawing and cabling technology.

3) Lateral offset $d = 2$ and 1 μm, the former corresponding to almost state of the art technology.

4) Tilt angle 0.2° as it seems to be readily feasible.

5) $L_s = 2.5$ km which should be attainable in the trunk network.

6) A continuous bending of the fiber in the cable with a radius of 20 cm (it turns out that this has no effect) and a localized bending of the fiber in the splicing pots with a radius of 5 cm. This last bending is assumed to be attained smoothly and without abrupt change from the cable bending and it affects 0.1 percent of the fiber length between splices. We thus have

$$\alpha_c = \alpha_c(R_c) + \alpha_c(R_s) \times 10^{-3} \tag{19}$$

where R_c and R_s are the radius of curvature in the cable and in the splicing pots, respectively, and $\alpha_c(R)$ is computed from (10)–(14).

We get the following:

$$\alpha_T = \alpha_i + \alpha_{SM} + \alpha_{SD} + \alpha_C. \tag{20}$$

A typical result for $\lambda = 1.3$ μm and $d = 2$ μm is shown in Fig. 2 where the shaded area is the usable surface as defined in Section III-A. The general shape of the surface is quite similar for the three other cases with displacements of the usable surface.

Before discussing the other cases, let us analyze the general shape of the surface; the very sharp rise for high λ/λ_c and small Δn is due to the curvature in the splicing pots and not in the cable. The less pronounced rise for small λ/λ_c and small Δn is due to microbending losses whereas the general increase for high Δn is due to both the Rayleigh scattering and the splicing loss. For high Δn values, there is a relative maximum notice-

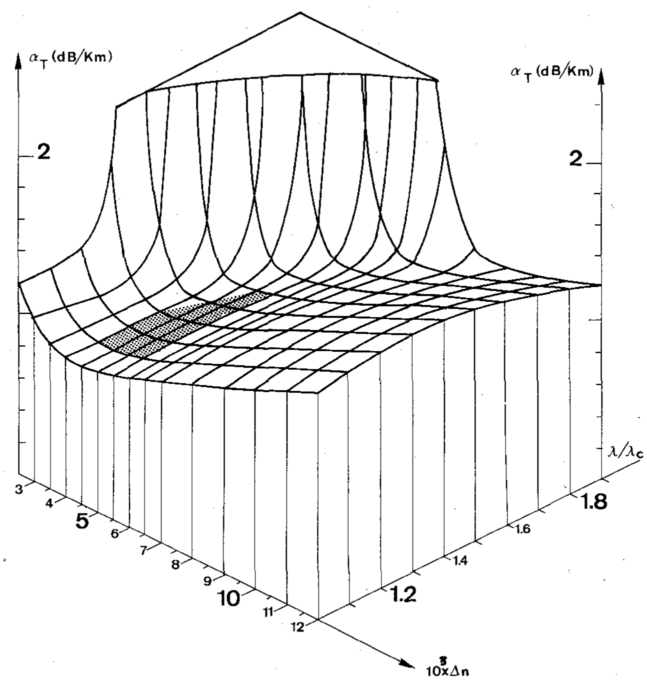

Fig. 2. Total loss α_T of the fiber laid in place as a function of λ/λ_c and Δn for $\lambda = 1.3$ μm, $d = 2$ μm, terrestrial system. The shaded area corresponds to the usable surface as defined in Section III-A.

able around $\lambda/\lambda_c = 1.3$, which is due to splicing loss as this value of λ/λ_c minimizes w_o for a given Δn.

Going to the other cases, we find that the optimum choice for $\lambda = 1.3$ μm common to $d = 2$ μm and $d = 1$ μm corresponds to a rectangular surface defined by

$$0.93\ \mu\text{m} \leqslant \lambda_c \leqslant 1.18\ \mu\text{m}$$

$$4.5 \times 10^{-3} \leqslant \Delta n \leqslant 5.5 \times 10^{-3}.$$

Looking now at the chromatic dispersion we find that it is less than 2 ps/nm · km (a residual value which can be easily compensated by a tolerable wavelength shift [14]) for

$$\lambda_c = 1.18\ \mu\text{m}; \quad 4.5 \times 10^{-3} \leqslant \Delta n \leqslant 5.5 \times 10^{-3}$$

$$\lambda_c = 1.08\ \mu\text{m}; \quad \Delta n = 4.5 \times 10^{-3}.$$

Looking now at the 1.55 μm wavelength and concentrating on the loss without care for the chromatic dispersion at this wavelength, we find that a common possible choice for all the terrestrial systems assumed here ($\lambda = 1.3$ or $1.55\ \mu m$; $d = 2$ or $1\ \mu m$) is

$$\lambda_c = 1.18\ \mu m, \qquad 5 \times 10^{-3} \leqslant \Delta n \leqslant 5.5 \times 10^{-3}.$$

(Again these are the nominal parameter values and the tolerances assumed in Section III-A can be accommodated for.)

The mean value of the transmission characteristics in the certainty surface around these nominal parameters is

$$\lambda = 1.3\ \mu m \quad \langle \mathcal{C} \rangle = -0.8\ \text{ps/nm} \cdot \text{km}$$

$$\langle \alpha_T \rangle (d = 2\ \mu m) = 0.90\ \text{dB/km}$$

$$\langle \alpha_T \rangle (d = 1\ \mu m) = 0.63\ \text{dB/km}$$

$$\lambda = 1.55\ \mu m \quad \langle \mathcal{C} \rangle = 16.5\ \text{ps/nm} \cdot \text{km}$$

$$\langle \alpha_T \rangle (d = 2\ \mu m) = 0.63\ \text{dB/km}$$

$$\langle \alpha_T \rangle (d = 1\ \mu m) = 0.42\ \text{dB/km}.$$

Obviously, at $1.55\ \mu m$ the fiber can only be used with monochromatic sources with or without heterodyne detection as the pulse broadening with a linewidth of 5 nm (three longitudinal modes in a semiconductor laser) would be intolerably high for long distance high bit rate transmission. Noticeable is the fact that improving the splicing technology for moving d from 2 to $1\ \mu m$ is as interesting as moving the wavelength from 1.3 to $1.55\ \mu m$ with the state of the art splicing technology (it is even more interesting if one takes dispersion into account). Fig. 3(a) summarizes the relative distances between repeaters, based on the total loss for the various cases.

C. Submarine Systems

For submarine systems, we consider the following situations:

1) $\lambda = 1.3$ and $1.55\ \mu m$.

2) $\alpha_{MM} = 0.15$ and 0.3 dB/km as the submarine cable properties are not yet well known, especially about the effect of tight buffering of the fiber.

3) Lateral offset $d = 2\ \mu m$ and tilt angle $0.2°$.

4) $L_S = 20$ km as continuous fibers of much greater lengths have been produced in laboratory (e.g., [5]).

5) Continuous bending of the fiber in the cable: 5 cm as some cable designs may require such a fiber bending for supporting the high cable elongation during cable layout and recovery.

A typical result for $\lambda = 1.55\ \mu m$ and $\alpha_{MM} = 0.3$ dB/km is shown in Fig. 4 where the shaded area corresponds to the usable surface as defined in Section III-A. The circle indicates a point with zero chromatic dispersion at $1.55\ \mu m$.

The conclusions are as follows:

The fiber with $\lambda_c = 1.18\ \mu m$ and $\Delta n = 5.5 \times 10^{-3}$ defined for terrestrial systems can be used for the submarine systems at $1.3\ \mu m$ (with the above assumptions). It can be used at $1.55\ \mu m$ only when $\alpha_{MM} = 0.15$ dB/km, and if the tolerances can be more tightly controlled.

A fiber usable for all the submarine systems considered here at both 1.3 and $1.55\ \mu m$ corresponds to

$$\Delta n = 6.5 \times 10^{-3}; \qquad \lambda_c = 1.18\ \mu m.$$

This fiber can also be used in terrestrial systems at $1.55\ \mu m$ ($d = 2$ or $1\ \mu m$) and at $1.3\ \mu m$ ($d = 1\ \mu m$). The corresponding performances are also shown in Fig. 3(a). This fiber has a dispersion of -1.5 ps/nm · km at $1.3\ \mu m$ and 15 ps/nm · km at $1.55\ \mu m$. The loss performances of this fiber in submarine systems are

$$\lambda = 1.3\ \mu m$$

$$\alpha_T(\alpha_{MM} = 0.3\ \text{dB/km}) = 0.59\ \text{dB/km}$$

$$\alpha_T(\alpha_{MM} = 0.15\ \text{dB/km}) = 0.56\ \text{dB/km}$$

$$\lambda = 1.55\ \mu m$$

$$\alpha_T(\alpha_{MM} = 0.3\ \text{dB/km}) = 0.39\ \text{dB/km}$$

$$\alpha_T(\alpha_{MM} = 0.15\ \text{dB/km}) = 0.34\ \text{dB/km}.$$

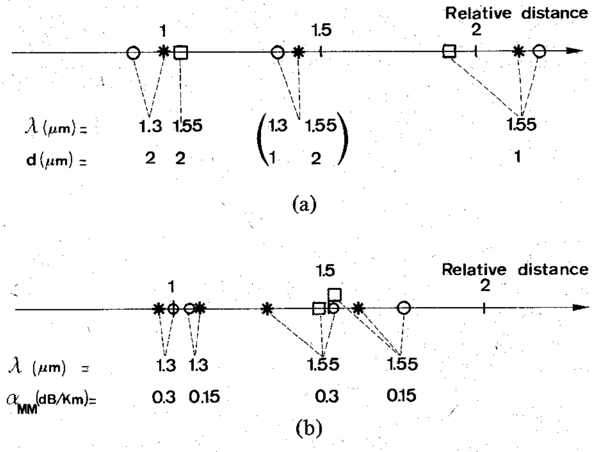

Fig. 3. Relative distances between repeaters based on loss. (a) Terrestrial systems. (b) Submarine systems. $*$: $\lambda_c = 1.18\ \mu m$; $\Delta n = 5.5 \times 10^{-3}$. $\circ$: $\lambda_c = 1.18\ \mu m$; $\Delta n = 6.5 \times 10^{-3}$. $\square$: $\lambda_c = 0.97\ \mu m$; $\Delta n = 1.1 \times 10^{-2}$.

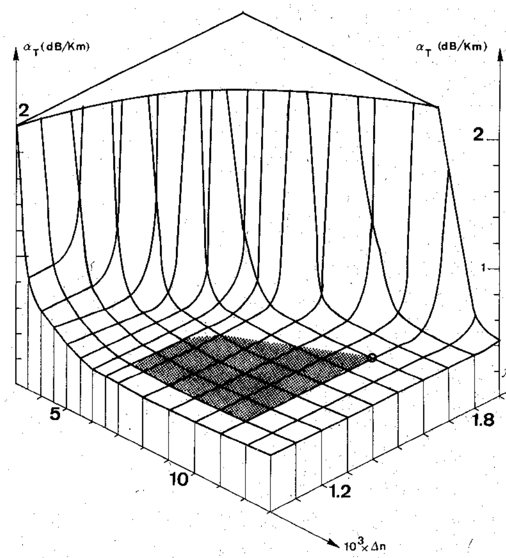

Fig. 4. Total loss α_T of the fiber laid in place as a function of λ/λ_c and Δn for $\lambda = 1.55\ \mu m$, $\alpha_{MM} = 0.3$ dB/km; submarine system. The shaded area corresponds to the usable surface as defined in Section III-A. The circle indicates a point with zero chromatic dispersion at $1.55\ \mu m$.

Fig. 3(b) shows the relative distances between repeaters, based on loss, for submarine systems for the two fibers of interest.

Again, at $1.55\ \mu m$ these fibers can be used only with monochromatic sources with or without heterodyne detection. It is therefore interesting to study a dispersion-free fiber at $1.55\ \mu m$.

D. Dispersion-Free Fiber at 1.55 μm

Comparing all the total loss surfaces at 1.55 μm as a function of λ/λ_c and Δn with the chromatic dispersion surface shows that the general optimum choice when $|\mathcal{C}| < 2$ ps/nm · km is imposed is the following:

$$\Delta n = 1.1 \times 10^{-2} \qquad \lambda_c = 0.97\ \mu\text{m}.$$

We do not change the tolerances considered up to now and we compute its mean dispersion in the certainty surface, which shows a value of

$$\langle \mathcal{C} \rangle = -\ 0.7\ \text{ps/nm} \cdot \text{km}.$$

The loss performances of this fiber in the various systems envisaged here are shown in terms of relative distance between repeaters in Fig. 3(a) and (b).

It appears from this figure that this fiber should be used only if monochromatic sources at 1.55 μm are not available as it generally degrades seriously the advantage of moving from 1.3 to 1.55 μm, and as its feasibility with ultimately low intrinsic loss as assumed by (3) is uncertain [2]. Furthermore, it is shown that this fiber presents no advantage over 1.3 μm fiber in terrestrial systems if $d = 2$ μm.

IV. Conclusion

By using accurate yet very simple approximations for the propagation characteristics of a step-index single-mode optical fiber, we have been able to provide a simple model for evaluating the influence of the structural parameters on the total loss and dispersion characteristics of a cabled, spliced, and laid down single-mode fiber transmission line for given operating conditions. This model has been applied to some terrestrial and submarine systems and the overall parameter optimization has been made by also taking into account economical aspects. The major results can be summarized as follows: starting from a state of the art technology which provides a splicing offset of 2 μm and no monochromatic sources at 1.55 μm, it is seen that there is no advantage in moving from 1.3 to 1.55 μm in terrestrial systems. In submarine systems, the same fiber as in terrestrial systems can be used for 1.3 μm but operation at 1.55 μm provides an increase of about 50 percent in the repeater spacing, provided the dispersion-free single-mode fiber at 1.55 μm can be reproducibly manufactured with the ultimate low loss assumed here.

Improving the splicing technology to yield a lateral offset of 1 μm makes the 1.55 μm wavelength also of interest to terrestrial systems as it provides an increase of 30 percent in the repeater spacing over the 1.3 μm wavelength with the same technology. Even at 1.3 μm the improvement between 2 and 1 μm splicing offset is about 40 percent.

The major breakthrough, however, would be to obtain monochromatic sources at 1.55 μm. It is seen that this makes the 1.55 μm wavelength interesting in all cases without the need for compensating dispersion. It can also be noticed that for each wavelength, the same fiber can be used in both terrestrial and submarine systems, or the 1.55 μm terrestrial systems could use the same fiber as that designed for 1.3 μm.

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