FIA Summer Seminar

Hot Topics

MFD mismatch

presented by

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Agenda

- What is MFD?
- Why is the fibre MFD important?
- Effects of an MFD mismatch:
  - As seen by a fibre splicer
  - As seen by an OTDR test engineer
  - Real issue or just perceived problem?

MFD – what is it?

- Mode Field Diameter (MFD) is a measure of the space occupied by light within a single-mode fibre
- size of the spot of light travelling in a fibre
- MFD is dependent on the wavelength of the light
- for a given standard fibre it is also dependent on the fibre NA & core diameter

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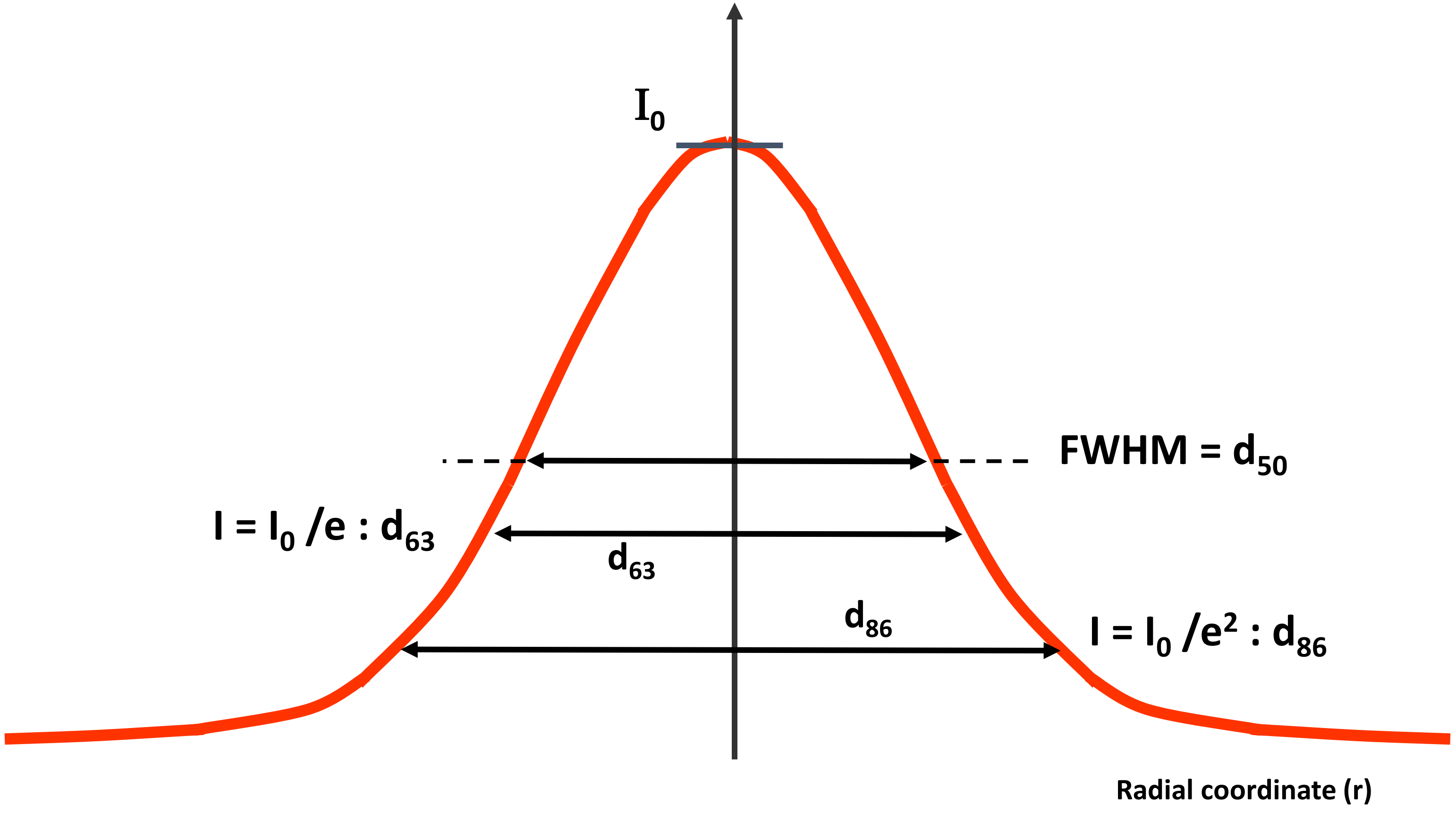
MFD definition

- width of a normal distribution?



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A visual representation courtesy of Commscope

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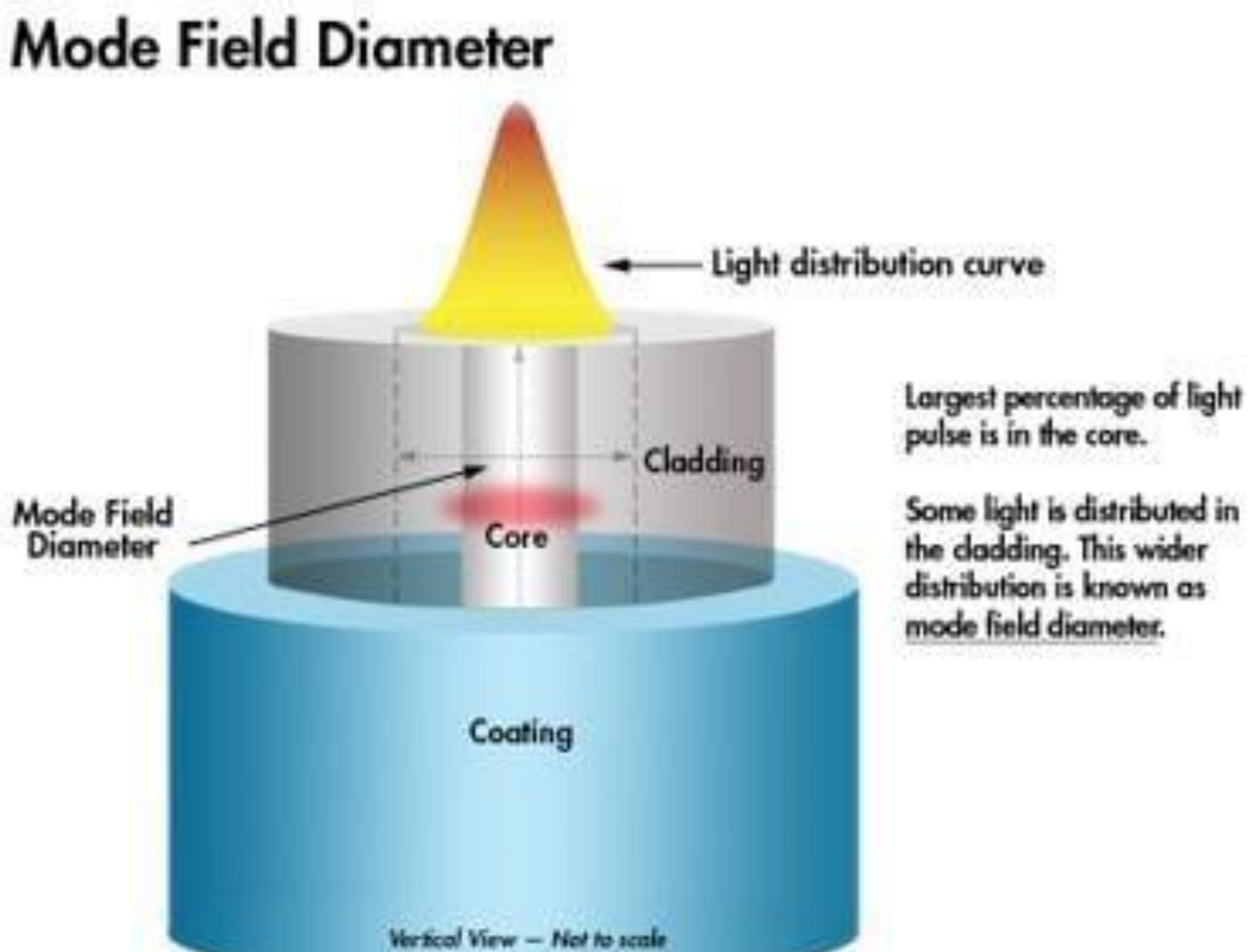

Typical MFD at 1550 nm

- Corning SMF-28 Ultra = 10.4 µm ± 0.5 µm
- OFS AllWave One Fiber = 10.4 µm ± 0.5 µm
- Corning LEAF = 9.6 µm ± 0.4 µm
- OFS TrueWave REACH = 8.6 µm ± 0.4 µm
- Corning ClearCurve LBL = 9.6 µm ± 0.5 µm
- OFS AllWave FLEX Max = 9.2 µm to 10.4 µm

MFD mismatch splicing issue

A splice with quite different single-mode fibre types

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Splicing dissimilar fibres

- is routinely done
- modern splicing machines can identify fibre types then -
- use appropriate splice parameters
- ensure splicing machine has latest firmware version

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OTDR – test outcome?

- apparent gain
- apparent loss
- true splice loss = average

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Real Issue?

- Yes, but to what extent?
- MFD mismatch results in excess loss
- Expected excess loss calculated using equations developed by D Marcuse (1977)
- Effectively an overlap function (convolution) of the two mode field profiles (diameters)
- Fusion splicing merges fibres at the splice point
- Excess loss is minimised

MFD mismatch issues are not new

- Has been understood by some in the industry for many years
- In 2002 Lightwave magazine published an article: **Impact of MFD mismatch on OTDR splice loss measurements** Sept. 1, 2002
- Authors: Gabor Kiss of Telcordia Technologies & Christopher Littlejohn of SAIC-Maripro
- Used an equation developed by Felix Kapron & colleagues at ITT to estimate the true loss from an MFD mismatch

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MFD mismatch table from Lightwave article 2002 based on equation from Felix Kapron 1986

Table 1. Detail of apparent and real loss

	MFD$_1$ = 8.8-micron non-DS fiber			MFD$_1$ = 7-micron DS fiber		
MFD$_2$ (microns)	Apparent loss	Backscatter contribution	Real loss	Apparent loss	Backscatter contribution	Real loss
8.3	-0.2391	-0.254	0.0148	0.8634	0.738	0.1253
8.4	-0.1926	-0.202	0.0094	0.9332	0.7896	0.1435
8.5	-0.1454	-0.1506	0.0052	1.0033	0.8406	0.1626
8.6	-0.0975	-0.0998	0.0023	1.0736	0.8909	0.1826
8.7	-0.0491	-0.0496	0.0006	1.1442	0.9405	0.2035
8.8	0	0	0	1.215	0.9895	0.2253
8.9	0.0496	0.0491	0.0006	1.286	1.038	0.2479
9	0.0998	0.0976	0.0022	1.357	1.086	0.2713
9.1	0.1505	0.1456	0.0049	1.429	1.133	0.2953
9.2	0.2016	0.193	0.0086	1.5	1.18	0.3202
9.3	0.2532	0.2399	0.0132	1.572	1.226	0.3456
9.4	0.3052	0.2864	0.0189	1.643	1.271	0.3718
9.5	0.3577	0.3323	0.0254	1.715	1.316	0.3985
9.6	0.4105	0.3777	0.0328	1.787	1.361	0.4259
9.7	0.4637	0.4226	0.0411	1.858	1.404	0.4538
9.8	0.5172	0.467	0.0502	1.93	1.448	0.4822

DS - Dispersion-shifted; MFD - Mode field diameter

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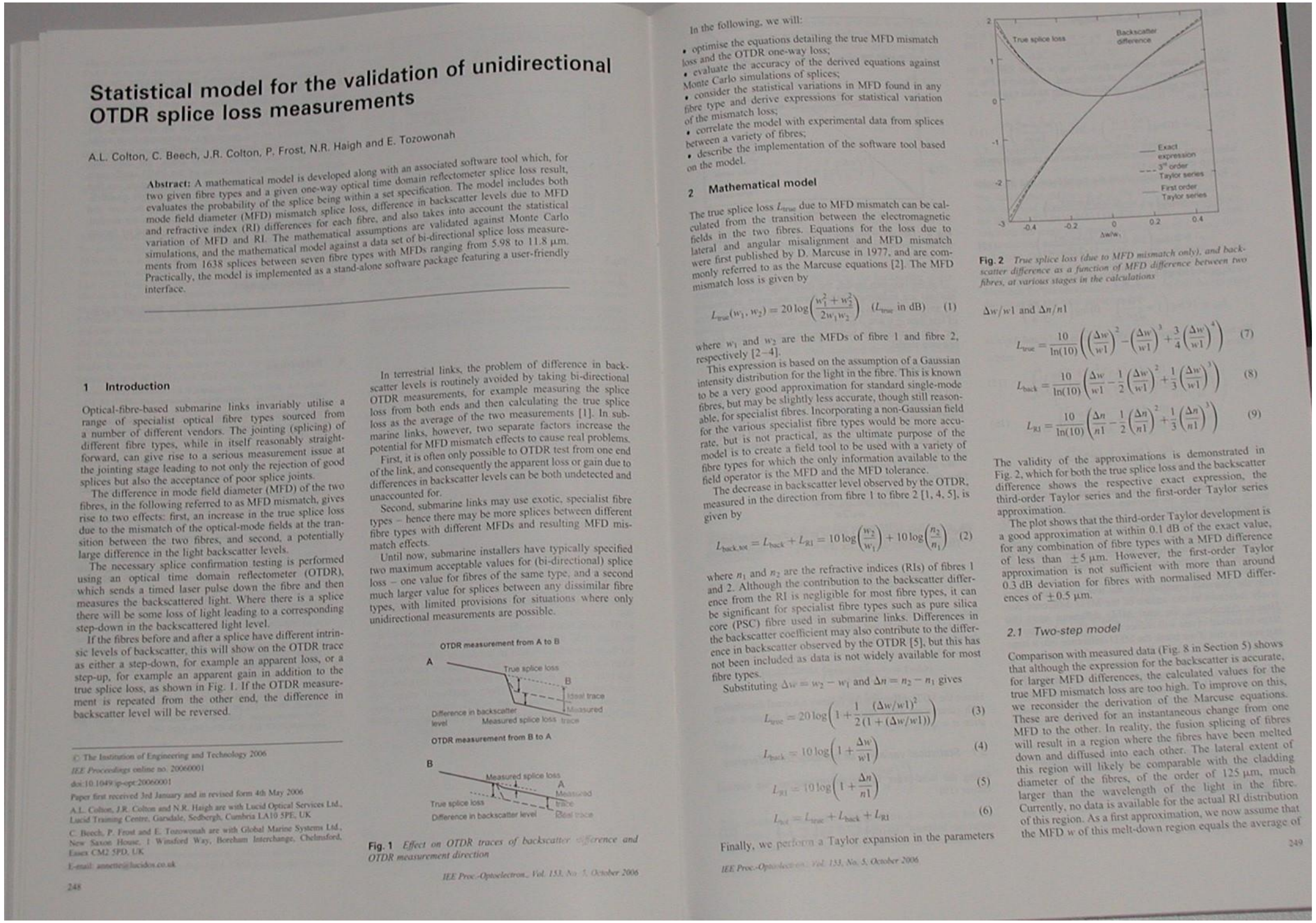
MFD mismatch importance?

- Problem often more perceived than real
- Can be real if splicing problems arise
- Real if the client objects to “MFD mismatch”
- Problematic if OTDR testing is unidirectional
- Aim to minimise “transition splices” in a link

New mathematical model for splice loss



Statistical model for the validation of unidirectional OTDR splice loss measurements

A.L. Colton, C. Beech, J.R. Colton, P. Frost, N.R. Haigh and E. Tozowonah

Abstract: A mathematical model is developed along with an associated software tool which, for two given fibre types and a given one-way optical time domain reflectometer splice loss result, evaluates the probability of the splice being within a set specification. The model includes both mode field diameter (MFD) mismatch splice loss, difference in backscatter levels due to MFD and refractive index (RI) differences for each fibre, and also takes into account the statistical variation of MFD and RI. The mathematical assumptions are validated against Monte Carlo simulations, and the mathematical model against a data set of bi-directional splice loss measurements from 1638 splices between seven fibre types with MFDs ranging from 5.98 to 11.8 µm. Practically, the model is implemented as a stand-alone software package featuring a user-friendly interface.

1 Introduction

Optical-fibre-based submarine links invariably utilise a range of specialist optical fibre types sourced from a number of different vendors. The jointing (splicing) of different fibre types, while in itself reasonably straightforward, can give rise to a serious measurement issue at the jointing stage leading to not only the rejection of good splices but also the acceptance of poor splice joints.

The difference in mode field diameter (MFD) of the two fibres, in the following referred to as MFD mismatch, gives rise to two effects: first, an increase in the true splice loss due to the mismatch of the optical-mode fields at the transition between the two fibres, and second, a potentially large difference in the light backscatter levels.

The necessary splice confirmation testing is performed using an optical time domain reflectometer (OTDR), which sends a timed laser pulse down the fibre and then measures the backscattered light. Where there is a splice there will be some loss of light leading to a corresponding step-down in the backscattered light level.

If the fibres before and after a splice have different intrinsic levels of backscatter, this will show on the OTDR trace as either a step-down, for example an apparent loss, or a step-up, for example an apparent gain in addition to the true splice loss, as shown in Fig. 1. If the OTDR measurement is repeated from the other end, the difference in backscatter level will be reversed.

In terrestrial links, the problem of difference in backscatter levels is routinely avoided by taking bi-directional OTDR measurements, for example measuring the splice loss from both ends and then calculating the true splice loss as the average of the two measurements [1]. In submarine links, however, two separate factors increase the potential for MFD mismatch effects to cause real problems.

First, it is often only possible to OTDR test from one end of the link, and consequently the apparent loss or gain due to differences in backscatter levels can be both undetected and unaccounted for.

Second, submarine links may use exotic, specialist fibre types – hence there may be more splices between different fibre types with different MFDs and resulting MFD mismatch effects.

Until now, submarine installers have typically specified two maximum acceptable values for (bi-directional) splice loss – one value for fibres of the same type, and a second much larger value for splices between any dissimilar fibre types, with limited provisions for situations where only unidirectional measurements are possible.

OTDR measurement from A to B

OTDR measurement from B to A

Fig. 1 *Effect on OTDR traces of backscatter difference and OTDR measurement direction*

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In the following, we will:

- optimise the equations detailing the true MFD mismatch loss and the OTDR one-way loss;
- evaluate the accuracy of the derived equations against Monte Carlo simulations of splices;
- consider the statistical variations in MFD found in any fibre type and derive expressions for statistical variation of the mismatch loss;
- correlate the model with experimental data from splices between a variety of fibres;
- describe the implementation of the software tool based on the model.

2 Mathematical model

The true splice loss L_{true} due to MFD mismatch can be calculated from the transition between the electromagnetic fields in the two fibres. Equations for the loss due to lateral and angular misalignment and MFD mismatch were first published by D. Marcuse in 1977, and are commonly referred to as the Marcuse equations [2]. The MFD mismatch loss is given by

$$L_{true}(w_1, w_2) = 20\log\left(\frac{w_1^2 + w_2^2}{2w_1w_2}\right) \quad (L_{true} \text{ in dB}) \qquad (1)$$

where w_1 and w_2 are the MFDs of fibre 1 and fibre 2, respectively [2–4].

This expression is based on the assumption of a Gaussian intensity distribution for the light in the fibre. This is known to be a very good approximation for standard single-mode fibres, but may be slightly less accurate, though still reasonable, for specialist fibres. Incorporating a non-Gaussian field for the various specialist fibre types would be more accurate, but is not practical, as the ultimate purpose of the model is to create a field tool to be used with a variety of fibre types for which the only information available to the field operator is the MFD and the MFD tolerance.

The decrease in backscatter level observed by the OTDR, measured in the direction from fibre 1 to fibre 2 [1, 4, 5], is given by

$$L_{back,tot} = L_{back} + L_{RI} = 10\log\left(\frac{w_2}{w_1}\right) + 10\log\left(\frac{n_2}{n_1}\right) \qquad (2)$$

where n_1 and n_2 are the refractive indices (RIs) of fibres 1 and 2. Although the contribution to the backscatter difference from the RI is negligible for most fibre types, it can be significant for specialist fibre types such as pure silica core (PSC) fibre used in submarine links. Differences in the backscatter coefficient may also contribute to the difference in backscatter observed by the OTDR [5], but this has not been included as data is not widely available for most fibre types.

Substituting $\Delta w = w_2 - w_1$ and $\Delta n = n_2 - n_1$ gives

$$L_{true} = 20\log\left(1 + \frac{1}{2}\frac{(\Delta w/w1)^2}{(1 + (\Delta w/w1))}\right) \qquad (3)$$

$$L_{back} = 10\log\left(1 + \frac{\Delta w}{w1}\right) \qquad (4)$$

$$L_{RI} = 10\log\left(1 + \frac{\Delta n}{n1}\right) \qquad (5)$$

$$L_{tot} = L_{true} + L_{back} + L_{RI} \qquad (6)$$

Finally, we perform a Taylor expansion in the parameters

True splice loss

Backscatter difference

Exact expression

3rd order Taylor series

First order Taylor series

$\Delta w/w_1$

Fig. 2 *True splice loss (due to MFD mismatch only), and backscatter difference as a function of MFD difference between two fibres, at various stages in the calculations*

$\Delta w/w1$ and $\Delta n/n1$

$$L_{true} = \frac{10}{\ln(10)}\left(\left(\frac{\Delta w}{w1}\right)^2 - \left(\frac{\Delta w}{w1}\right)^3 + \frac{3}{4}\left(\frac{\Delta w}{w1}\right)^4\right) \qquad (7)$$

$$L_{back} = \frac{10}{\ln(10)}\left(\frac{\Delta w}{w1} - \frac{1}{2}\left(\frac{\Delta w}{w1}\right)^2 + \frac{1}{3}\left(\frac{\Delta w}{w1}\right)^3\right) \qquad (8)$$

$$L_{RI} = \frac{10}{\ln(10)}\left(\frac{\Delta n}{n1} - \frac{1}{2}\left(\frac{\Delta n}{n1}\right)^2 + \frac{1}{3}\left(\frac{\Delta n}{n1}\right)^3\right) \qquad (9)$$

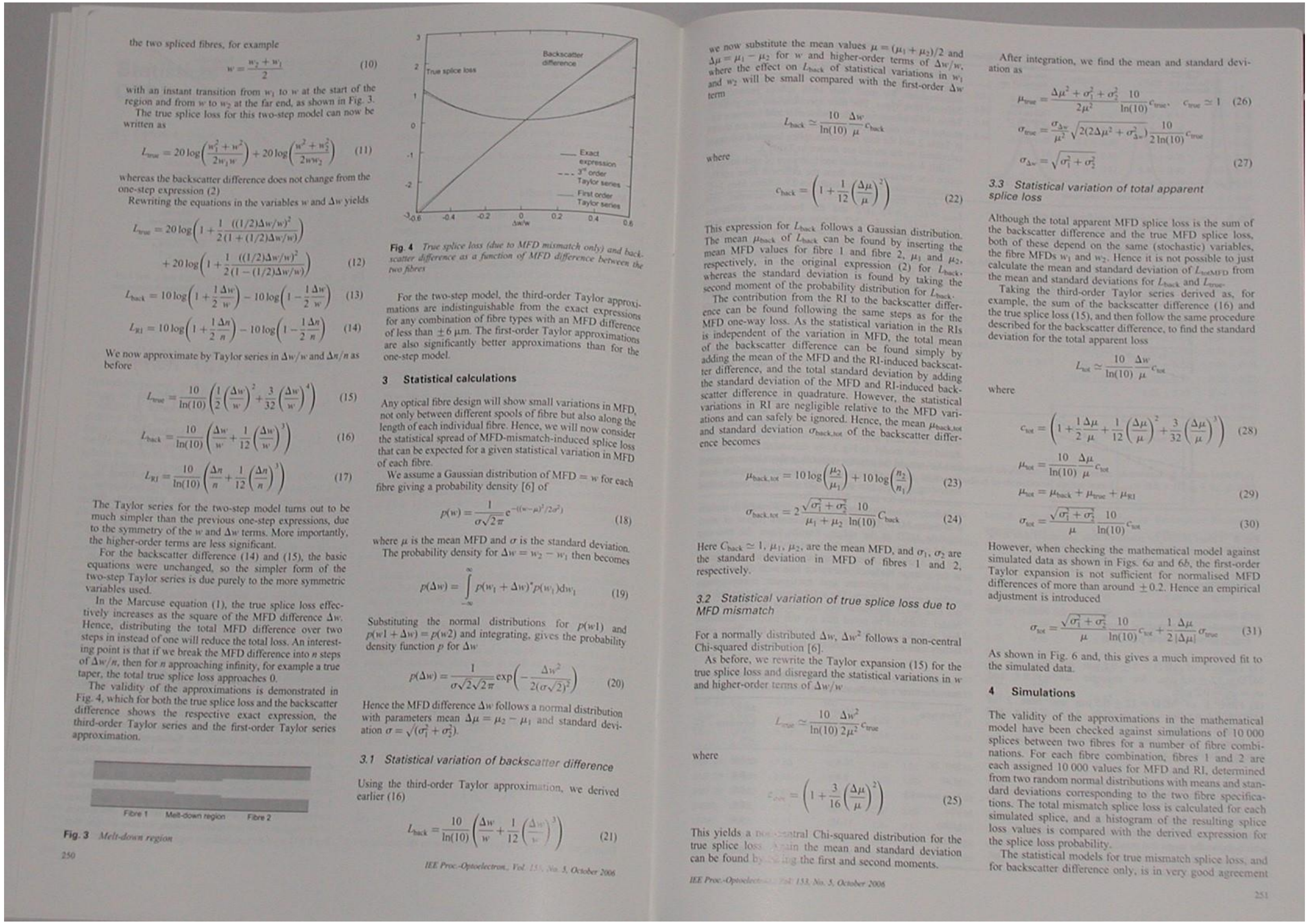
The validity of the approximations is demonstrated in Fig. 2, which for both the true splice loss and the backscatter difference shows the respective exact expression, the third-order Taylor series and the first-order Taylor series approximation.

The plot shows that the third-order Taylor development is a good approximation at within 0.1 dB of the exact value, for any combination of fibre types with a MFD difference of less than ±5 µm. However, the first-order Taylor approximation is not sufficient with more than around 0.3 dB deviation for fibres with normalised MFD differences of ±0.5 µm.

2.1 Two-step model

Comparison with measured data (Fig. 8 in Section 5) shows that although the expression for the backscatter is accurate, for larger MFD differences, the calculated values for the true MFD mismatch loss are too high. To improve on this, we reconsider the derivation of the Marcuse equations. These are derived for an instantaneous change from one MFD to the other. In reality, the fusion splicing of fibres will result in a region where the fibres have been melted down and diffused into each other. The lateral extent of this region will likely be comparable with the cladding diameter of the fibres, of the order of 125 µm, much larger than the wavelength of the light in the fibre. Currently, no data is available for the actual RI distribution of this region. As a first approximation, we now assume that the MFD w of this melt-down region equals the average of

Pages 3 & 4... and so on.



the two spliced fibres, for example

$$w = \frac{w_2 + w_1}{2} \quad (10)$$

with an instant transition from w_1 to w at the start of the region and from w to w_2 at the far end, as shown in Fig. 3.

The true splice loss for this two-step model can now be written as

$$L_{true} = 20\log\left(\frac{w_1^2+w^2}{2w_1 w}\right) + 20\log\left(\frac{w^2+w_2^2}{2ww_2}\right) \quad (11)$$

whereas the backscatter difference does not change from the one-step expression (2)

Rewriting the equations in the variables w and Δw yields

$$L_{true} = 20\log\left(1+\frac{1}{2}\frac{((1/2)\Delta w/w)^2}{(1+(1/2)\Delta w/w)}\right) + 20\log\left(1+\frac{1}{2}\frac{((1/2)\Delta w/w)^2}{(1-(1/2)\Delta w/w)}\right) \quad (12)$$

$$L_{back} = 10\log\left(1+\frac{1}{2}\frac{\Delta w}{w}\right) - 10\log\left(1-\frac{1}{2}\frac{\Delta w}{w}\right) \quad (13)$$

$$L_{RI} = 10\log\left(1+\frac{1}{2}\frac{\Delta n}{n}\right) - 10\log\left(1-\frac{1}{2}\frac{\Delta n}{n}\right) \quad (14)$$

We now approximate by Taylor series in $\Delta w/w$ and $\Delta n/n$ as before

$$L_{true} = \frac{10}{\ln(10)}\left(\frac{1}{2}\left(\frac{\Delta w}{w}\right)^2 + \frac{3}{32}\left(\frac{\Delta w}{w}\right)^4\right) \quad (15)$$

$$L_{back} = \frac{10}{\ln(10)}\left(\frac{\Delta w}{w} + \frac{1}{12}\left(\frac{\Delta w}{w}\right)^3\right) \quad (16)$$

$$L_{RI} = \frac{10}{\ln(10)}\left(\frac{\Delta n}{n} + \frac{1}{12}\left(\frac{\Delta n}{n}\right)^3\right) \quad (17)$$

The Taylor series for the two-step model turns out to be much simpler than the previous one-step expressions, due to the symmetry of the w and Δw terms. More importantly, the higher-order terms are less significant.

For the backscatter difference (14) and (15), the basic equations were unchanged, so the simpler form of the two-step Taylor series is due purely to the more symmetric variables used.

In the Marcuse equation (1), the true splice loss effectively increases as the square of the MFD difference Δw. Hence, distributing the total MFD difference over two steps in instead of one will reduce the total loss. An interesting point is that if we break the MFD difference into n steps of $\Delta w/n$, then for n approaching infinity, for example a true taper, the total true splice loss approaches 0.

The validity of the approximations is demonstrated in Fig. 4, which for both the true splice loss and the backscatter difference shows the respective exact expression, the third-order Taylor series and the first-order Taylor series approximation.

Fibre 1 Melt-down region Fibre 2

Fig. 3 Melt-down region

True splice loss
Backscatter difference
Exact expression
3rd order Taylor series
First order Taylor series
Δw/w

Fig. 4 True splice loss (due to MFD mismatch only) and backscatter difference as a function of MFD difference between the two fibres

For the two-step model, the third-order Taylor approximations are indistinguishable from the exact expressions for any combination of fibre types with an MFD difference of less than $\pm 6\,\mu m$. The first-order Taylor approximations are also significantly better approximations than for the one-step model.

3 Statistical calculations

Any optical fibre design will show small variations in MFD, not only between different spools of fibre but also along the length of each individual fibre. Hence, we will now consider the statistical spread of MFD-mismatch-induced splice loss that can be expected for a given statistical variation in MFD of each fibre.

We assume a Gaussian distribution of MFD $= w$ for each fibre giving a probability density [6] of

$$p(w) = \frac{1}{\sigma\sqrt{2\pi}} e^{-((w-\mu)^2/2\sigma^2)} \quad (18)$$

where μ is the mean MFD and σ is the standard deviation. The probability density for $\Delta w = w_2 - w_1$ then becomes

$$p(\Delta w) = \int_{-\infty}^{\infty} p(w_1 + \Delta w)^* p(w_1)\,dw_1 \quad (19)$$

Substituting the normal distributions for $p(w1)$ and $p(w1+\Delta w) = p(w2)$ and integrating, gives the probability density function p for Δw

$$p(\Delta w) = \frac{1}{\sigma\sqrt{2}\sqrt{2\pi}} \exp\left(-\frac{\Delta w^2}{2(\sigma\sqrt{2})^2}\right) \quad (20)$$

Hence the MFD difference Δw follows a normal distribution with parameters mean $\Delta\mu = \mu_2 - \mu_1$ and standard deviation $\sigma = \sqrt{(\sigma_1^2+\sigma_2^2)}$.

3.1 Statistical variation of backscatter difference

Using the third-order Taylor approximation, we derived earlier (16)

$$L_{back} = \frac{10}{\ln(10)}\left(\frac{\Delta w}{w} + \frac{1}{12}\left(\frac{\Delta w}{w}\right)^3\right) \quad (21)$$

we now substitute the mean values $\mu = (\mu_1+\mu_2)/2$ and $\Delta\mu = \mu_1 - \mu_2$ for w and higher-order terms of $\Delta w/w$, where the effect on L_{back} of statistical variations in w_1 and w_2 will be small compared with the first-order Δw term

$$L_{back} \simeq \frac{10}{\ln(10)}\frac{\Delta w}{\mu} C_{back}$$

where

$$C_{back} = \left(1 + \frac{1}{12}\left(\frac{\Delta\mu}{\mu}\right)^2\right) \quad (22)$$

This expression for L_{back} follows a Gaussian distribution. The mean μ_{back} of L_{back} can be found by inserting the mean MFD values for fibre 1 and fibre 2, μ_1 and μ_2, respectively, in the original expression (2) for L_{back}, whereas the standard deviation is found by taking the second moment of the probability distribution for L_{back}.

The contribution from the RI to the backscatter difference can be found following the same steps as for the MFD one-way loss. As the statistical variation in the RIs is independent of the variation in MFD, the total mean of the backscatter difference can be found simply by adding the mean of the MFD and the RI-induced backscatter difference, and the total standard deviation by adding the standard deviation of the MFD and RI-induced backscatter difference in quadrature. However, the statistical variations in RI are negligible relative to the MFD variations and can safely be ignored. Hence, the mean $\mu_{back,tot}$ and standard deviation $\sigma_{back,tot}$ of the backscatter difference becomes

$$\mu_{back,tot} = 10\log\left(\frac{\mu_2}{\mu_1}\right) + 10\log\left(\frac{n_2}{n_1}\right) \quad (23)$$

$$\sigma_{back,tot} = 2\frac{\sqrt{\sigma_1^2+\sigma_2^2}}{\mu_1+\mu_2}\frac{10}{\ln(10)} C_{back} \quad (24)$$

Here $C_{back} \simeq 1$, μ_1, μ_2, are the mean MFD, and σ_1, σ_2 are the standard deviation in MFD of fibres 1 and 2, respectively.

3.2 Statistical variation of true splice loss due to MFD mismatch

For a normally distributed Δw, Δw^2 follows a non-central Chi-squared distribution [6].

As before, we rewrite the Taylor expansion (15) for the true splice loss and disregard the statistical variations in w and higher-order terms of $\Delta w/w$

$$L_{true} \simeq \frac{10}{\ln(10)}\frac{\Delta w^2}{2\mu^2} C_{true}$$

where

$$C_{true} = \left(1 + \frac{3}{16}\left(\frac{\Delta\mu}{\mu}\right)^2\right) \quad (25)$$

This yields a non-central Chi-squared distribution for the true splice loss. Again the mean and standard deviation can be found by using the first and second moments.

After integration, we find the mean and standard deviation as

$$\mu_{true} = \frac{\Delta\mu^2+\sigma_1^2+\sigma_2^2}{2\mu^2}\frac{10}{\ln(10)} C_{true}, \quad C_{true} \simeq 1 \quad (26)$$

$$\sigma_{true} = \frac{\sigma_{\Delta w}}{\mu^2}\sqrt{2(2\Delta\mu^2+\sigma_{\Delta w}^2)}\frac{10}{2\ln(10)} C_{true}$$

$$\sigma_{\Delta w} = \sqrt{\sigma_1^2+\sigma_2^2} \quad (27)$$

3.3 Statistical variation of total apparent splice loss

Although the total apparent MFD splice loss is the sum of the backscatter difference and the true MFD splice loss, both of these depend on the same (stochastic) variables, the fibre MFDs w_1 and w_2. Hence it is not possible to just calculate the mean and standard deviation of L_{totMFD} from the mean and standard deviations for L_{back} and L_{true}.

Taking the third-order Taylor series derived as, for example, the sum of the backscatter difference (16) and the true splice loss (15), and then follow the same procedure described for the backscatter difference, to find the standard deviation for the total apparent loss

$$L_{tot} \simeq \frac{10}{\ln(10)}\frac{\Delta w}{\mu} C_{tot}$$

where

$$C_{tot} = \left(1 + \frac{1}{2}\frac{\Delta\mu}{\mu} + \frac{1}{12}\left(\frac{\Delta\mu}{\mu}\right)^2 + \frac{3}{32}\left(\frac{\Delta\mu}{\mu}\right)^3\right) \quad (28)$$

$$\mu_{tot} = \frac{10}{\ln(10)}\frac{\Delta\mu}{\mu} C_{tot}$$

$$\mu_{tot} = \mu_{back} + \mu_{true} + \mu_{RI} \quad (29)$$

$$\sigma_{tot} = \frac{\sqrt{\sigma_1^2+\sigma_2^2}}{\mu}\frac{10}{\ln(10)} C_{tot} \quad (30)$$

However, when checking the mathematical model against simulated data as shown in Figs. 6a and 6b, the first-order Taylor expansion is not sufficient for normalised MFD differences of more than around ± 0.2. Hence an empirical adjustment is introduced

$$\sigma_{tot} = \frac{\sqrt{\sigma_1^2+\sigma_2^2}}{\mu}\frac{10}{\ln(10)} C_{tot} + \frac{1}{2}\frac{\Delta\mu}{|\Delta\mu|}\sigma_{true} \quad (31)$$

As shown in Fig. 6 and, this gives a much improved fit to the simulated data.

4 Simulations

The validity of the approximations in the mathematical model have been checked against simulations of 10 000 splices between two fibres for a number of fibre combinations. For each fibre combination, fibres 1 and 2 are each assigned 10 000 values for MFD and RI, determined from two random normal distributions with means and standard deviations corresponding to the two fibre specifications. The total mismatch splice loss is calculated for each simulated splice, and a histogram of the resulting splice loss values is compared with the derived expression for the splice loss probability.

The statistical models for true mismatch splice loss, and for backscatter difference only, is in very good agreement

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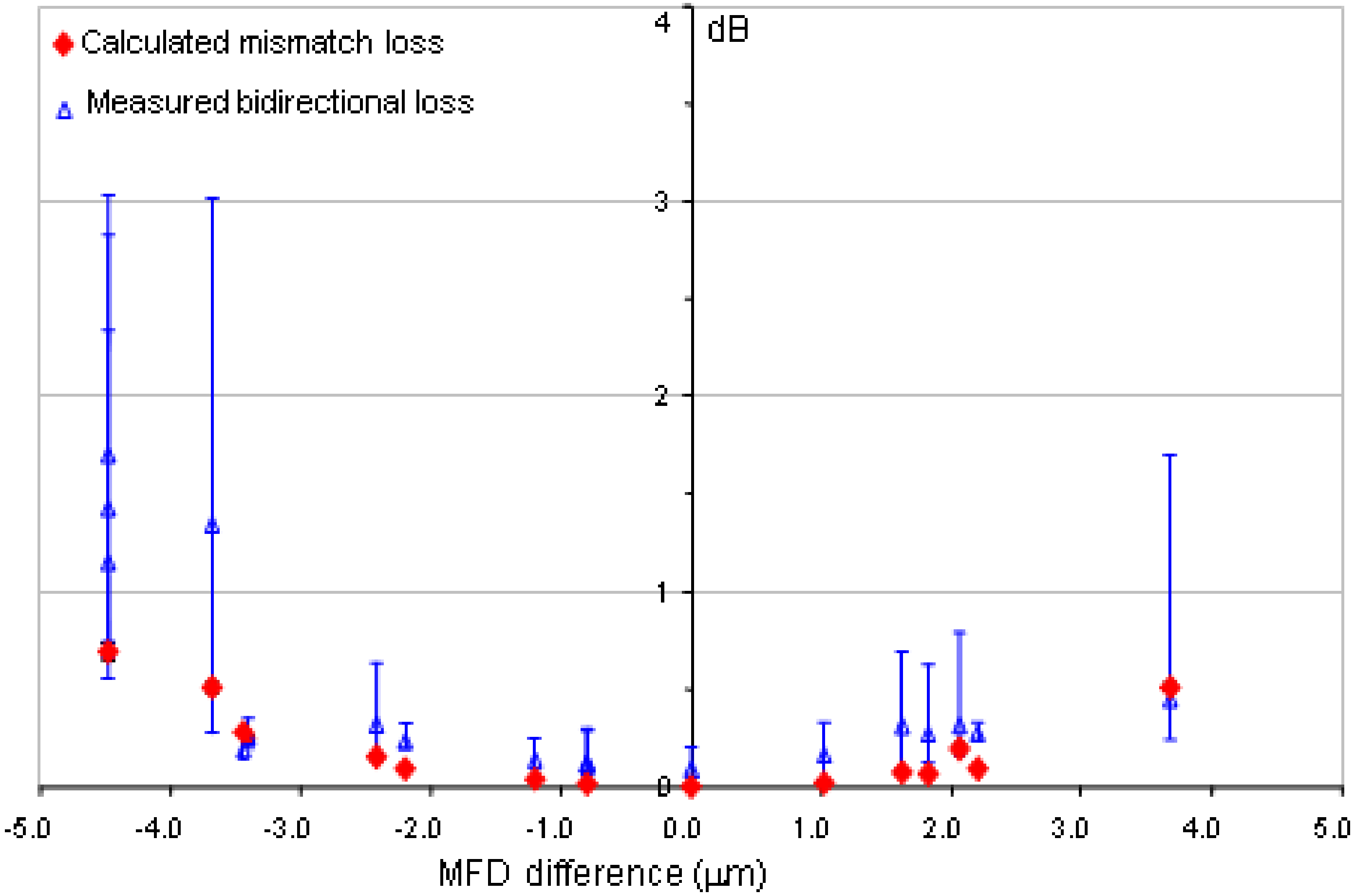
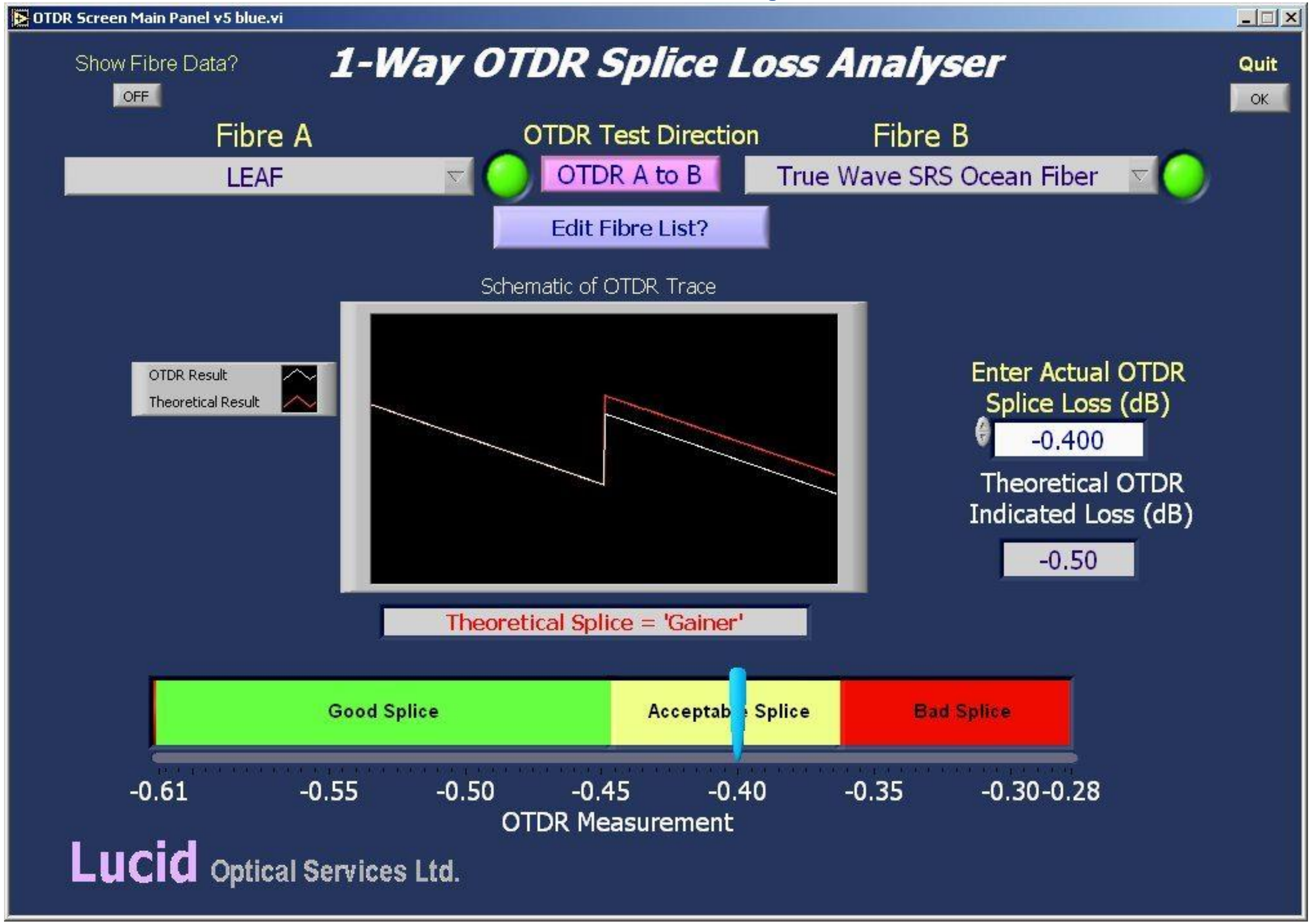
MFD mismatch excess loss – Lucid/Global Marine model versus measured data



Lucid/Global Marines Splice Loss Model



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