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EVALUATION OF CURVE-FITTING TECHNIQUES TO DETERMINE THE CUT-OFF WAVELENGTH OF SINGLE MODE FIBRES.

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ABSTRACT
An investigation has been made into the application of the ITU[1] recommended technique for curve-fitting Cut-off wavelength measurement data. Cut-off wavelength results of four fibre types have been analysed using the curvefitting technique. The results of this investigation indicate that the technique can reduce the standard deviation of such measurements by a factor of two, but the use of this technique is not always appropriate. The results for an improved technique are also presented.

INTRODUCTION
The growing demand for higher capacity in single mode fibre links, increases the need for improved accuracy in the measurement of the transmission properties of optical fibres. One important fibre parameter is the "Cut-Off Wavelength", the wavelength beyond which the fibre becomes single moded. The measurement of this parameter is problematic, principally because of the difficulty in defining the 0.1 dB point on the transmitted power plots measured in the Reference Test Method (RTM). To overcome this, curve-fitting routines have been developed and incorporated into the description of the RTM.

The ITU recommended technique for curve-fitting[1] has been assessed by applying it to the results of a European intercomparison between 10 laboratories of the cut-off wavelength measurements. Four types of optical fibre have been considered: Matched cladding, Depressed cladding, Dispersion shifted and erbium-doped active fibre.

CURVE-FITTING METHOD
The curve-fitting technique is based on a method described by Jacobs and Peckham. It is assumed that all spectral anomalies or "humps" in the $R(\lambda)$ plot are positive deviations from the true line. This has been confirmed in the literature[2]. The procedure is based on a theoretical model of the attenuation of the LP_{11} mode[3], and a method of fitting real data to that model.

Overview of the curvefitting method

The data is divided into 3 regions as illustrated in figure 1.

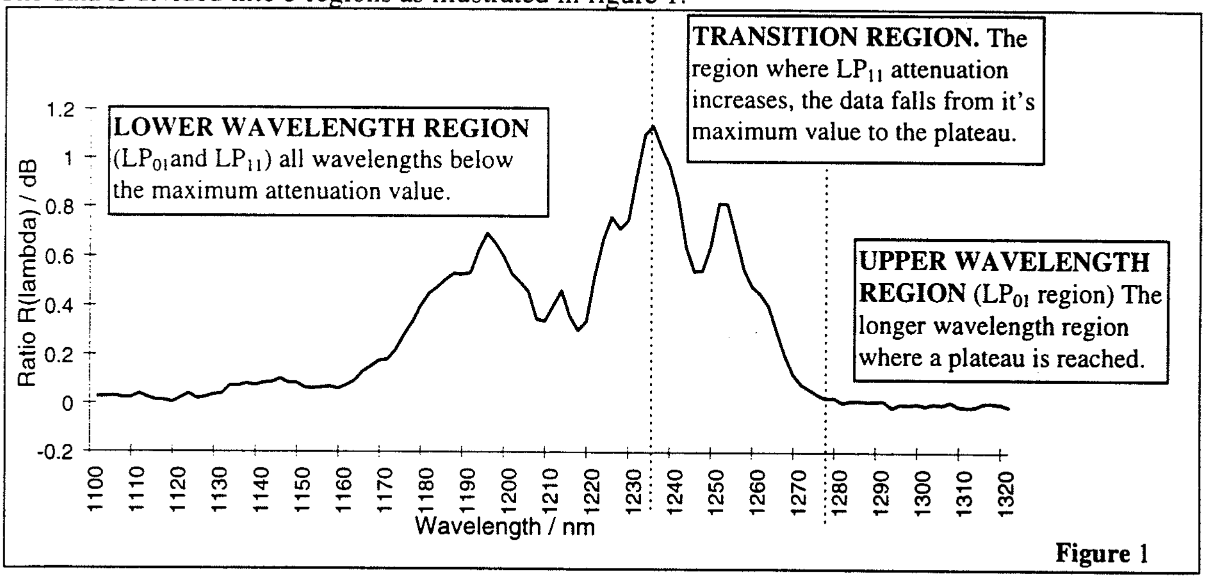

Figure 1

Data from the Lower Wavelength Region is not considered in this model.

The Upper Wavelength Region data is fitted to a straight line of zero gradient. The deviation of the true data from the fitted line is found and the maximum deviation is considered to be the maximum negative deviation that would be seen in the transition region.

The Transition Region can then be analyzed using simplex linear programming (i.e. several criteria which must be fulfilled simultaneously). The criteria of the fitted line are:

- The fit must follow the form (as shown by Okafor and Peckham[3]):

$$Y = 10\log\left[\frac{-10}{A}\log\left(\frac{10^{\Delta\alpha(\lambda)/10} - 1}{\rho}\right)\right] \quad \textbf{[1]}$$

where, A = 19.3 dB (attenuation of LP_{11} at cut off)
assuming that ρ = 2 (the ratio of launch powers LP_{11}/LP_{01})

- Negative deviations of the real data from the fit must be smaller than the Maximum Negative Error, as calculated in the upper wavelength region.
- Positive deviations of the real data from the fit can be any size, this allows for the possibility of "humps".
- The sum of all positive deviations should be minimised.
- The fit must coincide with the plateau at the intersection of the upper wavelength region and the transition region.

RESULTS

A program was written in Visual Basic to curve fit measured data using the technique described above. The data used for this investigation was forms the results of a European intercomparison of cut-off wavelength measurements of single mode fibres[4]. The results were obtained using the transmitted power measurement method.
The cut-off wavelength is defined as the longest wavelength where the ratio R(λ) is equal to 0.1dB where: $R(\lambda) = 10Log\left[P_1(\lambda)/P_2(\lambda)\right]$

P_1 = The transmitted power is measured through a 2 m sample of fibre
P_2 = The transmitted power though the sample with a 6 cm diameter, single loop mode filter

Over 100 data sets were analysed and in most cases the technique gave fits which closely followed the transmitted power curves. However, a number of anomalous cases have been observed. A summary of results for each fibre type follows:

MATCHED CLAD FIBRE:
The measurement results of the matched clad fibre exhibited small "humps" in the plateau region. The application of the curvefitting technique improved the standard deviation of these results from 7.4 nm to 3.5 nm. However the selection of the transition region is significantly influenced by the small changes in the size of the humps in the plateau region as shown in figure 2.

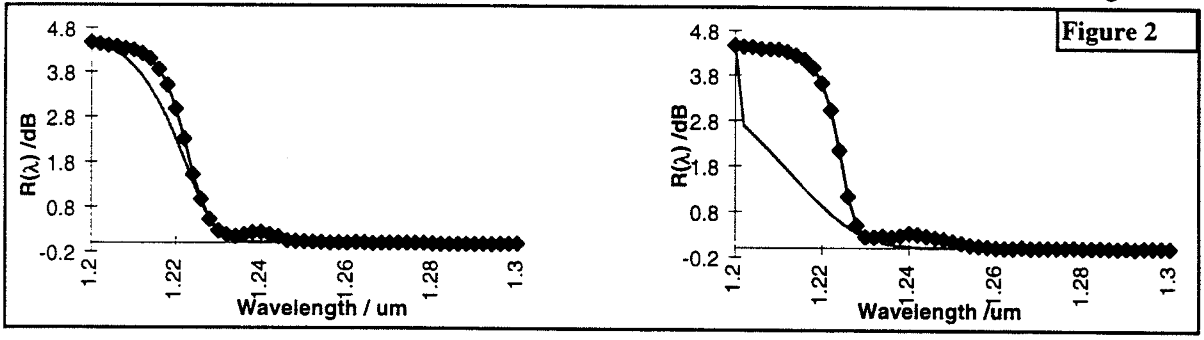

Figure 2

This indicates that improvements are required in the criteria for defining the transition region.

DEPRESSED CLAD FIBRE:
The curve-fitting technique improved the standard deviation of the measurement results from 3.1nm to 1.9 nm. However, when the fitting technique was applied to a set of results with larger variations in the features of the transition region, the standard deviation was increased 1.4 nm to 7.2 nm.

DISPERSION SHIFTED FIBRE:
These results illustrate the requirement to have measurement data that includes the wavelength where the maximum value of R(λ) occurs. This effect can be seen in figure 3, where the curve-fitting program again had difficulty in smoothing the deviations in the transition region.

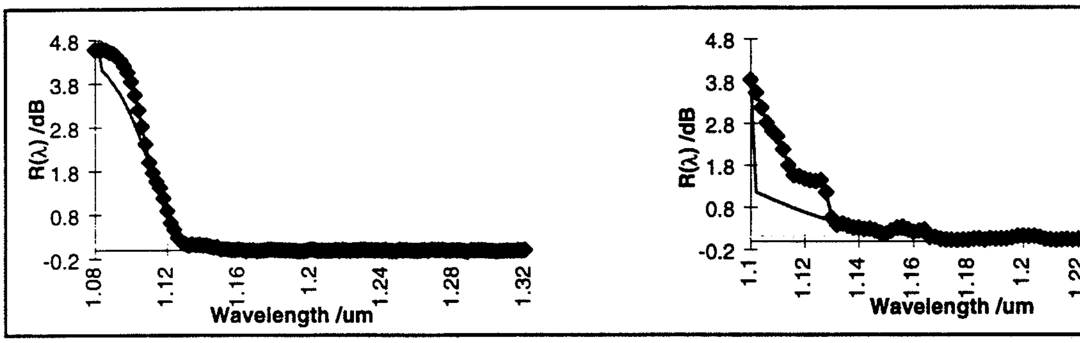

Figure 3

ACTIVE FIBRE:
The measurement results of the active fibres were very repeatable and applying the curve-fit gave no improvement in repeatability. However, the cut-off wavelength obtained from the curve fitting technique was 4 nm lower than from the standard method, suggesting that the empirical formula for the loop loss of the LP11 mode, which is incorporated into the Peckham formula model, does not fully model this fibre type.

IMPROVEMENTS TO THE ITU RECOMMENDED CURVE-FITTING TECHNIQUE

From the limitations described above the following improvements are suggested:
- Include data from wavelengths at least 20 nm before the attenuation peak and with at least 50 nm in the plateau.
- Amend the curve-fit to take into account data with humps on the plateau.
- Amend the curve-fit to take into account data with a flat attenuation peak.
- If the data is repeatable and shows no spectral anomalies, it is unnecessary to use the curve-fit.

RESULTS FROM IMPROVED CURVE-FIT

The curve-fitting method was modified to be more robust when humps are present on the plateau. This is achieved by calculating the gradient of the fitted curve in the Transition Region, then reducing the upper wavelength of the transition zone by one data point and recalculating that gradient. If the gradient changes significantly between the two calculations this indicates a hump on the plateau. The program reduces the upper wavelength of transition and recalculates the gradient until the change in gradient between adjacent data points is negligible. To more rigorously define the short wavelength limit of the Transition Region, the improved curve-fit determines the gradient at the lower wavelengths of the Transition Region and checks that it is steeper than -1. The short wavelength is incremented until this condition is met to ensure that the Transition Region starts on consistently defined downward slope of the R(λ) curve.

In matched clad, dispersion shifted and depressed clad fibres a further reduction in the standard deviation of results was seen when using the improved curve-fitting program. In matched clad fibres the standard deviation reduced from 3.5nm with the ITU recommended fit to 2.6 nm with the improved fit. For dispersion shifted fibre, the standard deviation was reduced from 8.9 nm to 7.3 nm and for depressed clad fibre from 1.9 nm to 1.8 nm. The improved curve-fit was not used on the active fibre results. The program compensated for humps on the plateau , a flat attenuation peak and the peak data not being included in the experimental results. Examples of the improved fit can be seen in figure 4.

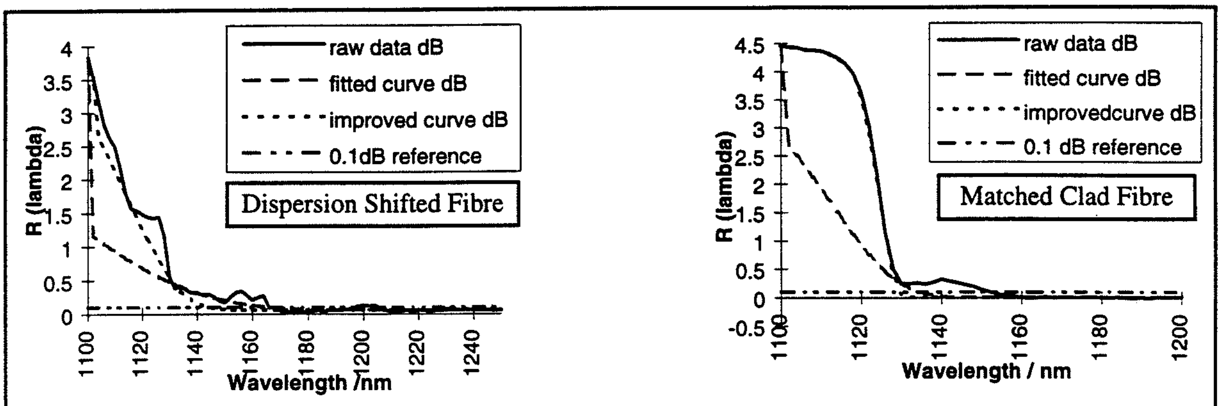

Figure 4

CONCLUSIONS

The precision of the ITU recommended curve-fitting technique in determining the cut-off wavelength of optical fibres is limited by: variation in the sensitivity to humps in the plateau region, limited wavelength data sets, large variations in the features in the transition region.

In addition, the empirical model used to determine the loop loss of the LP_{11} mode may not be valid for all fibre types.

A modified curve-fitting routine has been demonstrated to be less sensitive to some of the above effects.

ACKNOWLEDGEMENTS

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