Counting Modes in Optical Fibres with Leaky Modes

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Abstract: The number of guided modes in optical fibres is an important aspect of their design and characterisation. Some optical fibres, such as microstructured fibres and Bragg fibres, have no strictly bound modes in the same sense as in conventional step and graded index fibres. All modes in these fibres are leaky so what exactly becomes regarded as a mode becomes important.. We propose a method for counting the number of modes in fibres that takes into account the leaky nature of some modes. The method is based on the loss of each mode and the length of the fibre. This leads to a definition of singlemodedness for fibres with no bound modes.

1. Introduction: The definition of singlemodedness, and indeed what constitutes a mode is fundamental to optical fibres and almost all aspects of their characterisation. In conventional step and graded index fibres there are strict definitions for bound and leaky modes: bound modes are radially evanescent in the depressed cladding layer whilst leaky modes have oscillatory fields in the cladding, allowing power to leak out of the fibre [1]. Equivalently, bound modes are described by real mode effective indices and leaky modes are described by complex mode effective indices, where the loss is proportional to the imaginary part of the effective index [1]. In the case of step and graded index fibres the number of modes unambiguously refers to the number of bound modes, and when this equals one, the fibre is unambiguously single-moded.

For other types of optical fibres such as W-fibres, holey fibres [2] – microstructured optical fibres (MOFs) or photonic crystal fibres (PCFs)), band-gap fibres [3] – and Bragg fibres [4] there are no bound modes in this strict sense. In holey fibres the guiding mechanism is effective index guidance [5]; the core is surrounded by an arrangement of air holes that effectively produce a depressed index annulus around the core. In band gap fibres and Bragg fibres guidance is achieved by surrounding the core with a 2- or 1-dimensional photonic crystal. In both cases the structure around the core that provides the guiding mechanism is finite in extent and therefore the fibre only supports leaky modes. Since all modes in these fibres are leaky, quoting the number of modes guided by each fibre design becomes ambiguous. Many such fibres have been claimed to be single-moded but no convention exists to clarify the statement. We propose a method for counting the number of modes in these fibres that takes into account the loss of each leaky mode and the length of fibre in question. This method also sets out the conditions required for singlemodedness and outlines the requirements through which some fibres may be effectively single-moded though some or all modes are leaky.

2. Characterisation and Effective Singlemodedness: We outline below a method for characterising and counting *modes* and for characterising *fibres*. Using this, we set out criteria by which fibres can be effectively single moded whilst having no bound modes.

2.1 Characterising Modes: If the power in a mode is attenuated to less than 1% of its original value (i.e. by more than 20 dB) the mode is no longer deemed useful. If the power in a mode is attenuated to less than 0.01% of its original value (i.e. by more than 40 dB) the mode is considered to not exist. Modes attenuated between 20 and 40 dB can be considered to display low guidance. Using this, we can characterise each mode with two length values: $L_{1\%}$ represents the length required for that mode to be attenuated by 20 dB and $L_{0.01\%} = 2L_{1\%}$ represents the length required for that mode to be attenuated by 40 dB.

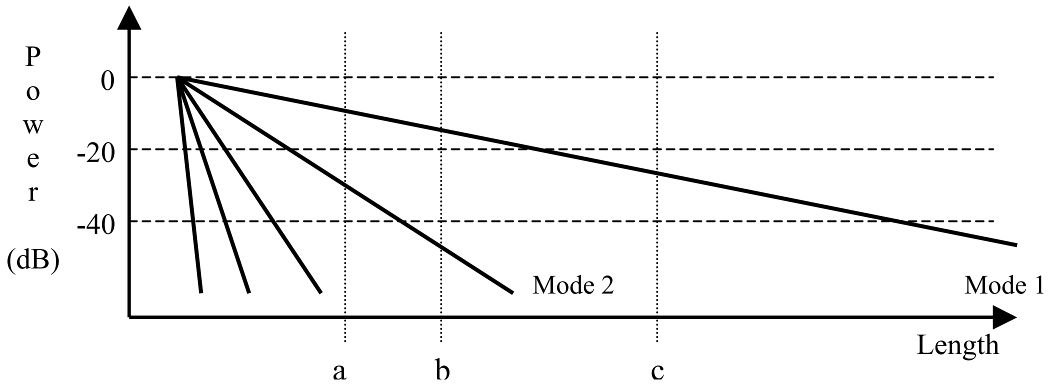
The values of 20 and 40 dB have been chosen somewhat arbitrarily, with the justification that amplifiers are capable of recovering signals attenuated by 30 dB. Thus, an attenuation of 20 dB represents a useful signal, in that it can be recovered easily, and an attenuation of 40 dB represents a signal that cannot be recovered, is effectively lost, and may be treated as non-existent.

2.2 Counting Modes in Fibres: Any given fibre will have a set of leaky modes and may have some bound modes. For a fibre of a given length, the guided modes will be those whose $L_{0.01\%}$ value is greater than the length of fibre. A useful amount of power will be transmitted in those modes that have $L_{1\%}$ greater than the length of the fibre (useful guidance). The modes whose $L_{1\%}$ is less than the length of the fibre but their $L_{0.01\%}$ is greater than the length of the fibre cannot be said to be either extinct nor useful with certainty and so are said to exhibit low guidance but not useful guidance. We believe that this transition stage between "useful" and "non-existent" needs to be present to strengthen the definition of effective singlemodedness below. For example, a 3 m long fibre with three leaky modes characterised by $(L_{1\%}, L_{0.01\%}) = (4, 8)$, $(2, 4)$ and $(1, 2)$ m will have two guided modes (the third mode will be lost) and will only have a useful amount of power in one mode (the first mode). The counting method is illustrated further in Fig. 1.

2.3 Characterising Fibres and Effective Singlemodedness: We can use the counting method outlined above to characterise a fibre as a whole using two length values, in a similar way to that of characterising the modes. The value L_{max} denotes the maximum length of fibre over which a useful amount of power can be transmitted in any mode. The value L_{max} is simply $L_{1\%}$ of the least leaky mode of that fibre. If the difference in the losses is sufficiently large and $L_{0.01\%}$ of the second least leaky mode is less than L_{max} then there will be a length of fibre over which only the least leaky moded is guided and all other modes have been attenuated enough to deem them non-existent. In this case the fibre only guides one mode and can be classified as effectively single-moded (see Fig. 1). In the effectively single-moded regime we do not allow low guidance modes to be present, as we cannot say with certainty that they will be sufficiently extinguished to eliminate modal dispersion. A second length L_{sm} denotes the length at which the fibre becomes effectively single-moded, and is equal to the $L_{0.01\%}$ value of the second least leaky mode. For a fibre to be effectively single-moded, the losses of the least and second least leaky modes must differ by a factor greater than 2 (when measured in dB/m) otherwise the value L_{sm} will be greater than the value L_{max} and no length of fibre will be effectively single-moded.

Matching the terminology used for standard fibres, we can allow the term "effectively single-moded" to include the case where there are actually two modes orthogonally polarised, with the same (or nearly the same) loss.

3. Theoretical Calculations and Experimental Results: We present below results from the literature as examples and to illustrate the applicability of the method outlined above. The first set of results reported in [6] are for a microstructured polymer optical fibre (MPOF) in which the core was surrounded with four hexagonal rings of holes – the four rings form the lower index region required for effective index guiding. The two least leaky modes of this structure as calculated in [6] are reproduced in Table 1(a). It can be seen that L_{sm} for this fibre is 0.2 m and L_{max} is 6.7×10^6 m (material absorption was not accounted for in the modelling). Samples of this fibre of length 1 m were experimentally found to be single-moded [6], consistent with our definitions.



Stage (a) Multimode 2 modes but 1 useful mode	Stage (b) Effectively Single-mode	Stage (c) 1 mode but 0 useful modes		
X	**X**		**Guided**	Useful Guidance Modes (< 20 dB attenuation)
X		**X**		Low Guidance Modes (> 20 dB but < 40 dB attenuation)
X X X…	**X X X…**	**X X X …**	**Lost**	Negligible Guidance Modes (> 40 dB attenuation)

20 dB

↓ Attenuation

40 dB

Figure 1. The graph above shows how the power in a set of modes would be attenuated along the fibre length. Three stages along the fibre are marked by the vertical lines and explained in the table to illustrate the mode counting method discussed. An "X" in each square indicates the presence of a mode that falls in the attenuation range indicated on the right column. In stage (a) there are 2 guided modes: 1 useful mode and 1 mode with low guidance. The number of lost modes is irrelevant. In stage (b) there is 1 useful mode and no low guidance modes so the number of guided modes is 1 and the fibre is effectively single-moded. Stage (c) has only one low guidance mode and the fibre is not considered to guide a useful amount of power.

The second set of results reported in [7] are for another MPOF, this time with three circular rings of holes surrounding the core. The calculations for the two least leaky modes are presented in Table 1(b). It can be seen that for this fibre $L_{sm} = 28$ m and $L_{max} = 1.1\mathrm{x}10^{3}$ m, once again material absorption was omitted. Experimentally, 20 cm lengths of this fibre were found to be single-moded whilst 5 cm lengths were found to be multimoded [7]. An explanation for the apparent inconsistency is given below.

These experimental results illustrate that our definitions, apart from forming a theoretical basis for describing fibres, also apply to experimental observations. These results show that single-modedness of fibres with no strictly bound modes, as treated in our definitions above, is a property that depends on the length of the fibre. The reason the experimental and theoretical results do not agree quantitatively is because of simplifications in the modelling – as with the

Table 1(a)

Mode Label	Loss (dB/m)	$L_{1\%}$ (m)	$L_{0.01\%}$ (m)	
1	$3x10^{-6}$	**$6.7x10^{6}$**	$1.3x10^{7}$	**L_{max}**
2	200	0.1	**0.2**	**L_{sm}**

Table 1(b)

Mode Label	Loss (dB/m)	$L_{1\%}$ (m)	$L_{0.01\%}$ (m)	
1	$1.9x10^{-3}$	**$1.1x10^{3}$**	$2.2x10^{3}$	**L_{max}**
2	1.48	14	**28**	**L_{sm}**

Table 1. (a) Calculations of the two least leaky modes of the fibre reported in [6]. (b) Calculations of the two least leaky modes of the fibre reported in [7]. The last two columns contain the two lengths that characterise each mode. The two lengths that characterise the fibres as a whole are in bold-face, with the corresponding label at the right of the table.

majority of fibre modelling, the fibre was assumed to be straight, with a perfect structure and a lossless material. We believe that quantitative agreement between theory and experimental observations can be reached with more accurate modelling, which includes material loss, scattering from hole surfaces, structural defects etc. Experimental observation of singlemodedness is independent of launch conditions since one of the tests for singlemodedness in [6,7] was to inspect the near field image of the mode and to observe that it remained unchanged as the launching conditions were changed.

4. Conclusion: We have presented a method for characterising leaky modes in fibres in terms of two lengths that represent the maximum length over which a mode is useful and the length required to extinguish the mode completely. This characterisation allows for the number of leaky modes guided in a fibre of given length to be counted unambiguously. This counting method in turn unambiguously defines effective singlemodedness for fibres with no bound modes. The fibre as a whole can be characterised in terms of a maximum useful length and, if applicable, a length required to attain singlemodedness.

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