

# Transition Loss in Bent Waveguides and Fibres

Jim Katsifolis

*Dept. of Electronic Engineering, La Trobe University, Bundoora, Victoria 3083, Australia*  
[j.katsifolis@ee.latrobe.edu.au](mailto:j.katsifolis@ee.latrobe.edu.au)

Shane Huntington

*School of Chemistry, University of Melbourne, Parkville, Victoria 3010, Australia*

Adrian Ankiewicz, John Love

*Research School of Physical Sciences, Australian National University, ACT 0200, Australia.*

Laurie Cahill

*Dept. of Electronic Engineering, La Trobe University, Bundoora, Victoria 3083, Australia*

We determine the origin of transition loss in bent waveguides and fibres. We show that transition loss can be suppressed, even in very tight bends provided that, in the geometrical transition from the straight to the bent waveguide or fibre, the local curvature is increased sufficiently slowly along the bend. Experimental results demonstrate this effect and are shown to be consistent with numerical simulations.

**Keywords:** bend loss, transition loss, beat length

## Introduction

When a straight single-mode fibre or waveguide enters a bend, it is well known that power is radiated from the fundamental mode into the cladding as it propagates along the bend. The total radiated power along the bend can be expressed in terms of a superposition of two physically different effects, namely pure bend loss and transition loss. Pure bend loss is associated with the radiation of fundamental mode power from each position along the bend and is independent of the transition from the straight to the bent waveguide [1]. Conversely, transition loss is normally associated with the abrupt change in curvature between the straight and bent waveguides and its contribution to overall bend loss occurs over a relatively short distance along the bend.

Pure bend loss has been investigated in detail by many authors and can be quantified using a number of different analytical techniques. As a result, approximate analytical expressions are available for pure bend loss from e.g. step-profile slab waveguides [2] and fibres [1].

Transition loss arises from the mismatch between the fundamental mode fields of the straight and bent waveguides or fibres. For a bent waveguide, the effect of curvature is to introduce a small offset in the fundamental mode that displaces its field slightly outwards relative to the centre of the bend in the plane of the bend. As a result of this shift, not all of the incident mode power of the straight waveguide is transmitted into the fundamental mode on the bend. The power that is lost excites the non-guided field and thus forms part of the radiation field of the bent fibre.

Although the radiation loss from the fundamental mode is continuous along the bend, the superposition of the transition loss can lead to the generation of discrete beam radiation within the bend region. This effect was first reported by Gambling et al [3] using a coiled fibre stripped of its coating and immersed in a cladding-index matching liquid. It was subsequently investigated by others during an early study of loss from curved single mode fibres [4][5]. Their analyses suggested that; (i) the beam phenomenon was due to a beating effect between the fundamental mode and a dominant higher-order leaky mode that is quasi-guided by the bend, and (ii) the coupling between the fundamental and leaky modes was caused by the constant-radius bend.

In this paper we show that, although the beams are due indeed to a beating effect as previously observed, the effect is actually induced by the relatively rapid increase in curvature from the beginning of the bend, rather than by the constant-radius bend itself. We also show that it is possible to suppress excitation of the leaky mode and therefore the discrete beams, even in a tight bend, by introducing a transition region leading into the bend with a sufficiently slow increase in curvature.

## Numerical Simulation

Bend loss in fibres and waveguides occurs predominantly in the plane of the bend. Accordingly it is adequate for the present investigation to model bend loss from a single-mode bent waveguide and thereby simplify the complexity of the numerical simulation. The 2-dimensional bent step-profile waveguide is then replaced by a straight graded 1-dimensional waveguide using a standard conformal transformation. The effect of this transformation is to tilt the refractive index profile. Thus, by varying the tilt of the profile either abruptly or continuously along the waveguide, the effect of a jump or continuous increase in curvature on propagation can be quantified. The numerical quantification of bend loss and the radiation field along the bends was simulated using Olympios BPM software. In each case the fundamental mode field of the straight waveguide was launched at the beginning of the bend.

Results showed the presence of discrete beam radiation occurred along bends where there was an abrupt or relatively fast change in curvature. Where the change of radius of curvature was minimized, the discrete beam radiation was also minimized or effectively suppressed. These results are plotted in Figure 1 for a bend radius of 2.1mm.

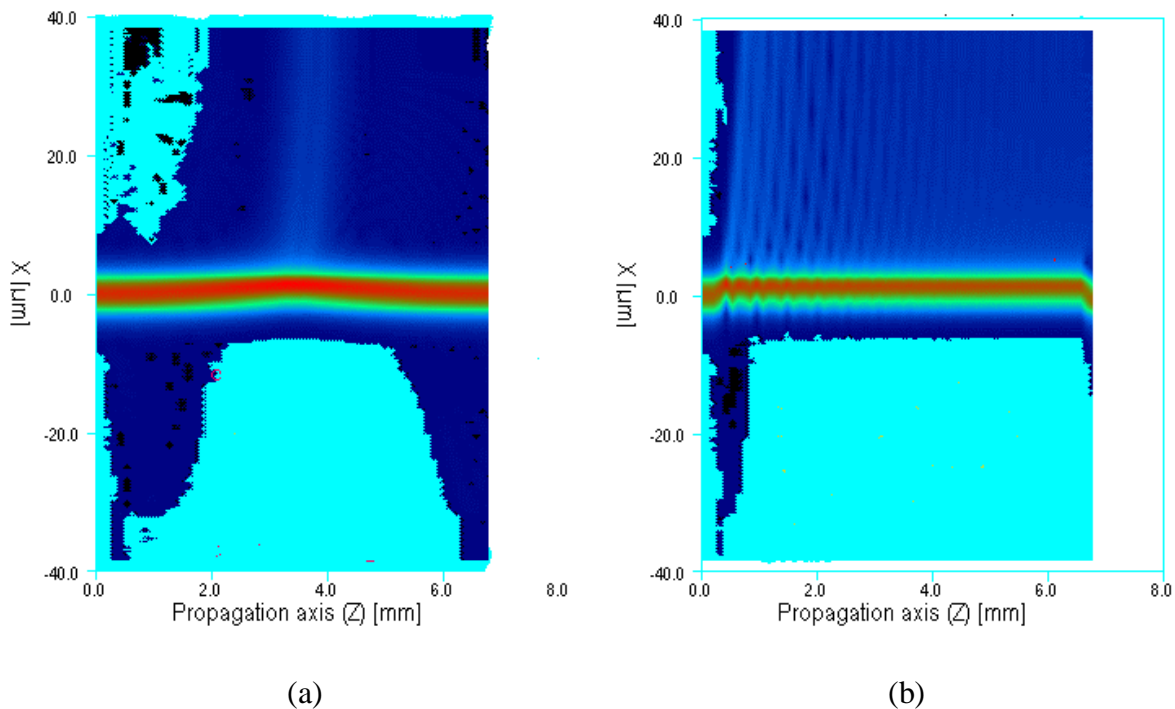


Figure 1: Simulation results for slab waveguides. In (a), the waveguide is bent into a parabolic curve with a low rate of curvature change everywhere along its length, and no discrete beam radiation is present. In (b) the parabolic curve has a more rapid change in curvature at the beginning of the bend, and discrete beam radiation is now present.

The simulation results in Figure 1(a) show that even for a tight parabolic bend there are no discrete beams generated, since there is only a low rate of change in the radius of curvature. Only continuous radiation due to pure bend loss is present. In the case where there is a more abrupt change in curvature radius, as in Figure 1(b), the higher-order leaky mode is excited at this transition point, and the resultant beating between this mode and the fundamental along the bend generates the set of discrete beams.

### Experimental Investigation

Several single-mode fibres were bent into different radii and, after removal of the coating, were immersed in an oil medium with a slightly higher refractive index than the cladding in order to view any discrete radiation. In each experiment only the fundamental mode of the fibre was excited.

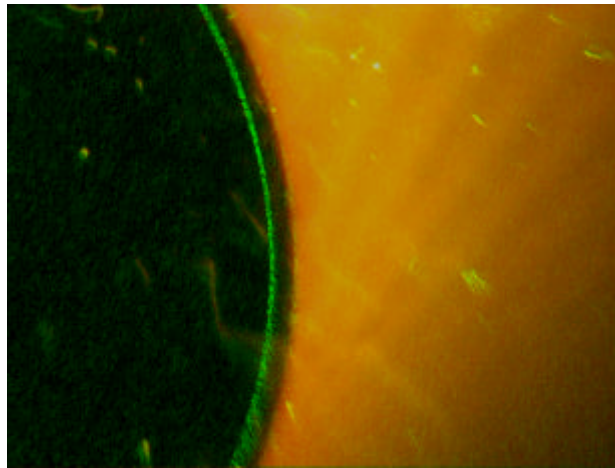


Figure 2. Discrete beam radiation from a single-mode fibre bent into a semi-circular arc of 1.5mm radius.

Figure 2 shows the discrete beam radiation from a single-mode fibre bent in a semi-circular arc with uniform radius of 1.5mm. The measured beat length between the beams is approximately 180 microns and is consistent with the numerical simulation, allowing for the difference between modal effective indices between the fibre and slab geometries. The discrete beams can be accounted for by the fairly abrupt change of curvature between the straight part of the fibre and the circular bend. The abruptness couples power from the fundamental mode into the leaky second mode and the two modes beat together to generate the discrete beams.

This phenomenon is illustrated better in Figure 3, where a near single-mode fibre is bent into a 180° parabolic-shape bend with a low rate of curvature change at any point along its length. Using a fibre with a higher V-value allows discrete beam radiation to be observed at larger bend radii for the same excitation wavelength. Only the fundamental mode is excited in the straight part of the fibre.

In Figure 3(a), no discrete beams are present and only the expected continuous radiation due to pure bend loss from the fundamental mode is present. In Figure 3(b), the lead-in fibre is straightened slightly so that a small transition region with more abrupt change in curvature is introduced close to the beginning of the parabola. In this case, discrete beam radiation is again clearly evident.

A more detailed and quantified analysis of transition loss will be presented at the conference, including a criterion for minimising transition loss.

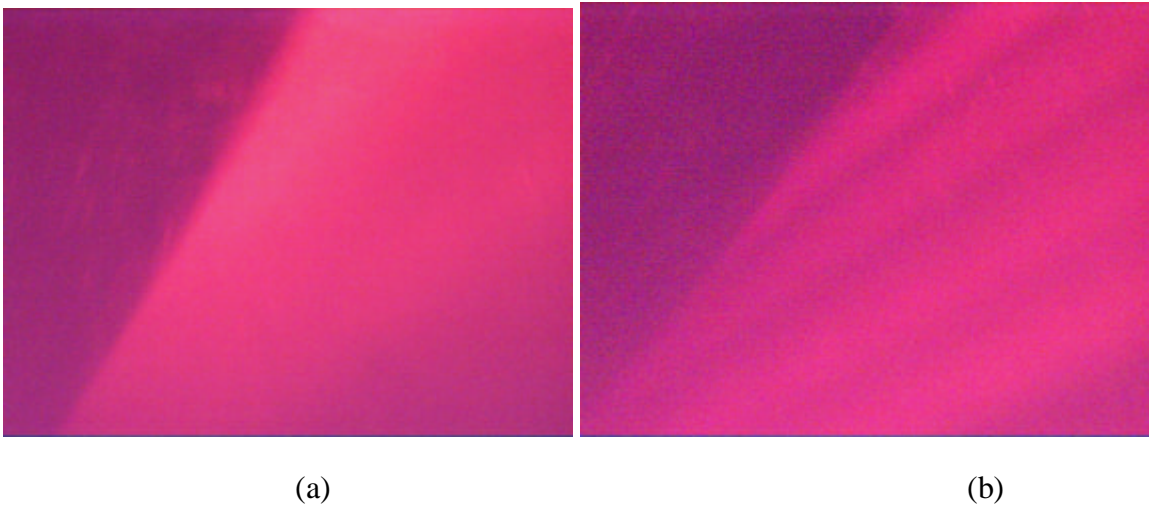


Figure 3 A fibre bent into a 180° parabolic bend shape. In (a), no discrete beam radiation is present due to the low rate of change in curvature along the fibre. In (b) the lead in fibre is straightened slightly to give a more abrupt change in curvature and discrete beam radiation is now present.

## Conclusions

The origin of discrete beams observed in the radiation field of bent single-mode waveguides and fibres has been shown to be due to the coupling of power from the fundamental mode to the first leaky along the bend. Such coupling only occurs when the bend curvature changes rapidly along the bend and can be virtually suppressed by introducing a sufficiently slow change in curvature.

This prescription allows, in particular, for the design of transition-loss free waveguide bends with a smooth variation in curvature, and provides an alternative to the standard practice of inserting an offset between the straight and bent waveguide cores in the case of an abrupt change in curvature.

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