Out-of-plane scattering in 1D photonic crystal slabs.

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Abstract
We present a detailed study of out-of-plane scattering losses in a 1D approximation of 2D photonic crystal slabs. In 2D photonic crystals with a waveguide structure in the third dimension, the periodic structure (in a lot of applications a 2D arrangement of holes etched through the core and cladding) will cause light to scatter out of the waveguide plane. We studied the out-of-plane scattering losses of these holes using a 2D approximation of this 3D structure, with etched slots instead of holes. Our simulation techniques included mode expansion with PML and FDTD. We will present the influence of the refractive index contrast between core and cladding of the layered structure. We show that the losses increase with higher index contrast between core and cladding, but that with very high index contrasts and under the right circumstances light can be coupled into lossless Bloch modes.

Key Words:
Photonic Crystals, Out-of-plane Scattering, Guided Bloch mode

1. Introduction

One of the most promising applications of photonic crystals today is the use of two-dimensional crystal structures in combination with a layered waveguide in the third dimension to provide refractive index guiding. In typical structures [2, 8] the photonic crystal consists of air holes etched into a semiconductor slab waveguide, well into the bottom cladding. Light with wavelengths within the bandgap of the photonic crystal could be confined in a channel waveguide in the lattice (e.g. a missing row) or other types of defects [1], or light with wavelengths outside the bandgap could propagate as a Bloch mode of the periodic structure [5, 7, 6]. In either case the light will feel the effect of the etched air holes, where there is no refractive index contrast in the vertical direction. These air holes can be a cause of loss in the waveguide due to a lack of index guiding and scattering of light out of the waveguide plane, either into the air or into the substrate. A good understanding of these losses could allow us to treat 2D photonic crystals with vertical index guiding as a pure 2D problem, where the out-of-plane scattering losses are modeled as a complex refractive index in the holes, thereby relaxing the need for full 3D modeling of 2D photonic crystals [3].

Two approaches have been suggested to reduce these scattering losses. In a first approach one uses a conventional heterostructure, like a GaAs-$Al_xGa_{1-x}As$ combination, which has a modest to low refractive index contrast for the vertical guiding. As suggested by Bénisty et al. [2, 3], losses increase with the square of ??, where ??? n_{core}^2 ? n_{clad}^2, with n_{core} and n_{clad} the refractive index of the slab waveguide's core and cladding respectively. This approach requires that the holes are infinite, or at least etched deep enough for the guided slab mode not to feel the bottom of the holes, so they shouldn't cause parasitary scattering.

Another approach is to maximize the index contrast of the slab waveguide, even to a limit where high index material (e.g. Silicon, GaAs,…) is suspended in air (a so-called membrane). A more practical material would be Silicon on Insulator (SOI) with an index contrast of about 3.5 to 1.45. These high index contrasts make it possible to create periodic structures with Bloch modes below the light line, that is, modes that have no radiation losses whatsoever [5, 7, 6]. However, these Bloch modes can only be lossless in an infinite periodic structure, while photonic crystal applications will always be finite and/or have defects where out-of-plane scattering can occur. Another drawback of this approach is that high contrast structures invariably need an insulator cladding, which severely compromises the possibilities to fabricate active devices.

We studied the losses of a 2D approximation of the full 3D structure. Our simulation structure consists of a 3-layer slab waveguide with air slots etched through the structure, as illustrated in figure 1. The air holes of 2D periodic structures are replaced with infinite air slots. This approach has the limitation that light cannot 'flow around' the air holes as it would in 2D photonic crystals, and that therefore losses will be higher than with a 2D lattice.

We will show here that by increasing the refractive index contrast between core and cladding of the waveguide structure, we will indeed observe an increase of scattering losses as predicted by Bénisty et al. [2, 3], but that these losses drop again when a lossless Bloch mode is excited when the contrast becomes high enough.

The remainder of the paper is structured as follows. In section 2 we briefly discuss the simulation principles we used for our calculations. Section 3 describes the losses of a single air slot, which can be regarded as an incoherent source of out-of-plane scattering. In section 4 we present the results for multiple air slots and we show how the coherent effects can reduce the out-of-plane scattering for high index contrasts.

2. Simulation tools and structures

2.1 Simulation technique

To calculate the characteristics of the optical structures under consideration, we used our simulation tool CAMFR [4], which is based on vectorial eigenmode expansion and perfectly matched layer (PML) boundary conditions. The structure is divided into sections with a constant refractive index profile along the propagation axis, and the field in each of these sections is expanded onto the eigenmodes of that particular section. In order to get a discrete set of radiation modes; the structure is placed between two perfectly conducting metal walls. These walls are coated with PML, so as to eliminate the parasitic reflections from them, thereby effectively simulating an open structure. At the interfaces between different waveguide sections, mode matching is used to decompose the field into the eigenmodes of the new section, which ultimately gives rise to a scattering matrix describing the entire structure. This technique allows us to calculate reflection and transmission of finite structures, but is also suited for the calculation of band structures for infinite periodic structures, by imposing Bloch boundary conditions in the propagation direction.

We also used the much slower FDTD-technique [9] as a verification tool.

2.2 SLAB WAVEGUIDE LAYER STRUCTURE

As semiconductor appears to be the most popular candidate for 2D photonic crystals, we tried to approach common semiconductor heterostructures. We chose for a three-layer slab waveguide (top cladding, waveguide core and bottom cladding) with a core thickness d_{core} of 0.225?m and a refractive index n_{core} of 3.5. The slab waveguide of figure 1 is invariant in the *x*-direction. The slab waveguide is single mode at a wavelength of 1.55?m for all values of n_{clad}, and the guided mode of the slab waveguide propagates in the *z*-direction. We then vary the waveguide cladding index n_{clad} to study the behavior with different refractive index contrasts. This change in index contrasts obviously alters the dispersion relation of this waveguide and also the band structure of a periodic structure etched into the waveguide.

For the remainder of this text, the refractive index contrast will be expressed as ? ? ? n_{core}^2 ? n_{clad}^2 . Some values of ? ? correspond with real layer structures. A maximum ? ? of 11.25 corresponds to a silicon membrane with air cladding. A silicon core in an oxide cladding has a ? ? value of 10, while a low-contrast GaAs-$Al_xGa_{1-x}As$ heterostructure has a ? ? of about 2.

3. Single air slot

When we limit the problem to the scattering of a single air slot in the slab waveguide, we can treat this as the incoherent limit where each hole radiates independently of the other holes, and scattering losses of individual holes or slots are accumulated. This approximation allows us to verify our result with the model recently proposed by Bénisty et al [1], where scattering losses in the air holes are treated as independently radiating dipoles.

Figure 2 shows the losses of a single air slot with a width d_a of 0.28?m. Reflection and transmission of the guided mode are also plotted. Simulations of the losses of a single air slot confirm the notion that out-of-plane scattering increases with higher refractive index contrast. For very low index contrast the losses increase with the square of ? ?, as predicted by Bénisty et al. [6]. Moreover, the radiation of a single air slot is very similar to a two dimensional dipole, again as predicted in [2]. For higher refractive index contrasts, the relationship ceases to be quadratic, and the losses level out. Therefore when one is working in the region of low to medium index contrast (e.g. an GaAs-$Al_xGa_{1-x}As$ heterostructure) it might be beneficial to keep the refractive index contrast as low as possible, for a small increase in the refractive index of the waveguide cladding might yield a considerable drop in losses. For high refractive index contrasts (Semiconductor membranes in air, or Silicon-on-insulator,…) a change in refractive index of the cladding is far less important from the viewpoint of out-of-plane scattering losses.

4. Multiple slot losses

Photonic crystals are periodic structures, so treating the losses of each air hole in an incoherent manner might seem overly simplistic. As shown in [5, 7], a 2D periodic structure can have totally lossless Bloch modes, when the scattering losses of each of the holes interfere destructively. Our simulations show that a similar guided lossless Bloch mode can also be supported by a 1D periodic structure.

We studied the structure sketched in figure 1, with a period P of 0.55?m and an air slot width d_a of 0.28?m. These parameters are chosen so that at a wavelength ? of 1.55?m the periodic structure behaves very differently depending on the refractive index contrast between core and cladding of the slab waveguide. Figure 3 shows the band structure of the infinite 2D structure for different index contrasts between core and cladding layers. The shaded region bounded by the light line indicates the continuum of the radiation modes. Figure 4 shows the propagation constants of the Bloch modes at ?=1.55?m with increasing refractive index contrast. We see that for high contrasts the structure quickly changes between 4 distinct regimes. In figure 3a (?? = 2.0, typical for a GaAs-$Al_xGa_{1-x}As$ heterostructure) we are obviously working outside of a bandgap and above the light line, and we expect out-of-plane scattering losses to increase with increasing refractive index contrast, since the light can easily couple to the radiative continuum. These losses are plotted in figure 5 as a function of the refractive index contrast ??. When working outside of the bandgap, the characteristics of a periodic structure are a non-monotonous function of the number of periods. This can also be observed e.g. when considering the position and amplitude of the sidelobes in the reflection spectrum of a DBR for different periods. To eliminate these fluctuations, we took the average of the losses of the periodic structures with 30 to 50 periods.

At an index contrast of ??=10.00 (figure 3b) the infinite periodic structure has a region below the light line for high values of k_z. However, there is no guided mode present in this region.

At a slightly higher index contrast of ??=10.92 (figure 3c) there is a guided mode below the light line at the wavelength of 1.55?m. For an infinite periodic structure, this mode would be lossless, i.e. the mode would have no radiation losses. This is only true for an infinite structure, or in close approximation for the bulk of a finite periodic structure. We see in figure 5 that losses have dropped sharply in this region, and the transmission of the structure has increased dramatically. Most of the losses in this regime can be attributed to transition losses at the interface between the homogeneous slab waveguide and the periodic structure.

For even higher refractive indices (figure 3d) there are again no guided modes below the light line, but there is a bandgap at the operating wavelength. Most of the incident light is now reflected in the first few periods and doesn't penetrate the structure. Therefore losses are also quite low in this regime, and can again be credited to transition losses at the boundary of the periodic structure.

We plotted the losses of these four structures as a function of the number of periods N in figure 6. For each set of data we added a broad moving average. As expected, for low index contrast (? ? = 2.0) we find low losses per slot, but the total loss increases as more slots are added. For a higher index contrast of ? ?=10.00 losses per hole are much higher, and we need only a few holes for all the light to be lost (the remaining light is reflected). If there is a guided Bloch mode at the operating wavelength, the only losses we observe are coupling losses from the slab mode to the Bloch mode and back, so as expected the losses remain constant regardless of the number of periods, as does the transmission. If we operate within the bandgap of the structure, most incident light is reflected back into the waveguide within the first few periods, so losses remain constant as we add more periods. However, transmission quickly drops to zero in this regime.

5. Conclusions and perspectives

Losses due to out-of-plane scattering put a limitation to the usefulness of 2D photonic crystal slabs. Designing the optimum layer structure to keep these losses low is therefore an important step in the design of these structures. We have shown that if we treat the losses of each hole independently, losses increase with the square of ? ? for low refractive index contrasts, as predicted by Bénisty [3]. For higher refractive index contrasts, these losses level out.

We also studied the out-of-plane scattering losses of a periodic structure with multiple air slots. We can distinguish 4 different regimes for such a structure. For low refractive index contrasts, the behavior is similar as with the single air slot. Losses increase with increasing refractive index contrasts. For high contrasts losses will be very high unless one can excite a lossless Bloch mode below the light line [6], resulting in a drop in out-of-plane scattering losses and a higher transmission of the structure. If one operates in a bandgap of the photonic crystal below the light line, losses will be low because light cannot penetrate the crystal.

From the perspective of out-of-plane scattering, two regimes seem to be favorable to reduce undesired losses, depending on the application. For applications with many defects close to each other, the best way to go is a low refractive index contrast between core and cladding. If one has few and/or widely separated defects, it might be preferable to couple light into a lossless Bloch mode and use a high refractive index contrast.

For this paper, we calculated the losses of a 1D periodic structure with infinite air slots. This is an approximation of slots that are etched very deep into the bottom cladding of the slab waveguide, where the guided mode is sufficiently confined to the waveguide core. Additional losses are to be expected when the slots aren't etched deep enough or with insufficient confinement, e.g. when the index contrast is too low. For realistic structures in the low contrast regime, one will therefore have to balance between keeping a low index contrast (material choice) and the depth of the air slots (etching facilities) to keep the losses as low as possible. In the high index contrast regime, one can target a regime where the losses in the bulk of the periodic structure can theoretically be reduced to zero. However, applications using these structures will always require defects that will introduce losses in the otherwise lossless structure.

Acknowledgements

Parts of this work is supported by the European Union in the context of the IST project PICCO

Parts of this work were also carried out in the context of the Belgian DWTC project IUAP IV-13.

Wim Bogaerts acknowledges the Flemish Institute for the industrial advancement of Scientific and Technological Research (IWT) for a specialisation grant

Peter Bienstman acknowledges the Flemish National Fund for Scientific Research (FWO-Vlaanderen) for a doctoral fellowship.

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Figure Captions

FIGURE 1:

Geometry of the simulated structure. A symmetric 3 layer slab waveguide periodically intersected with air slots. The structure is invariant in the *x*-direction. The slab waveguide is single mode at a wavelength of 1.55?m for all values of n_{clad}.

FIGURE 2:

Out-of-plane scattering losses for a single air slot with a width d_a=0.28?m. For low ?? the losses increase with the square of ?? (as indicated by the dotted curve), but level out at high index contrasts. The inset shows the reflection and transmission of the guided mode.

FIGURE 3:

Band structures of the structure in figure 1 for different refractive index contrasts. Only the first half Brillouin zone is drawn here. Photonic bandgaps are indicated with coarse shading. The continuum of radiation modes above the light line is shaded gray. The operating wavelength of 1.55 ?m is also indicated.

FIGURE 4:

Mode propagation constants at a wavelength of 1.55?m for the structure in figure 1 with increasing refractive index contrast. The 4 cases of figure 3 are marked a through d. Only the first half Brillouin zone is drawn.

FIGURE 5:

Reflection, Transmission and out-of-plane scattering loss for the structure of figure 1 as a function of refractive index contrast ??. The values are averaged over a structure with 30 to 50 periods to eliminate oscillations related to the finite number of periods. The 4 cases outlined in figure 3 are marked a through d. The oscillations between ??=6 and ??=10 are a numerical phenomenon related to imperfect absorption of the PML boundary.

FIGURE 6:

Out-of-plane scattering losses as a function of number of periods *N*. The 4 cases from figure 3 are plotted along with a moving average. For low contrasts (a), losses are low but increase slowly with each added period. For higher contrasts (b) the losses climb rapidly and reach a maximum after only a small number of periods. Only the reflected power is not lost. As a guided Bloch mode is excited (c) the losses remain constant regardless of the number of periods. When we operate within the bandgap, only a few periods are needed to reflect most of the power back into the waveguide and the losses remain constant with the number of periods.

FIGURE 1

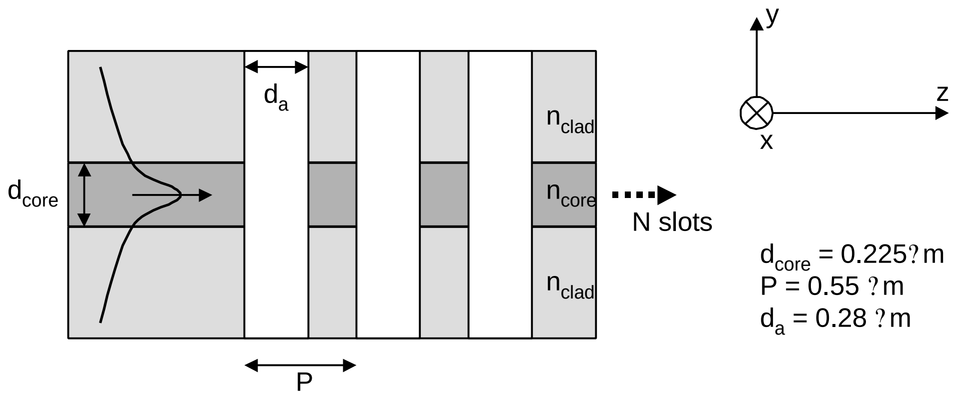
y
z
x
d_a
n_clad
d_core
n_core
N slots
n_clad
P
d_core = 0.225?m
P = 0.55 ?m
d_a = 0.28 ?m

FIGURE 2

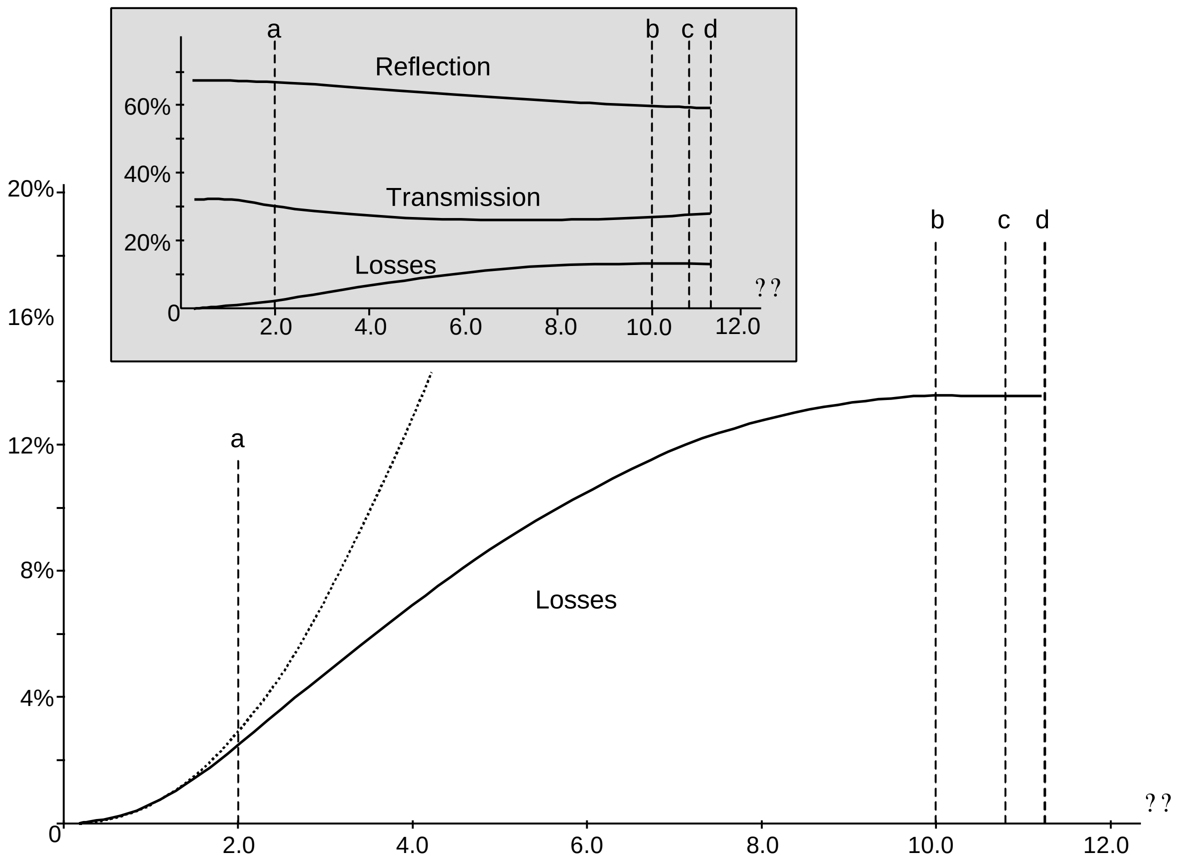
a
b
c
d
Reflection
Transmission
Losses
60%
40%
20%
0
2.0
4.0
6.0
8.0
10.0
12.0
? ?
20%
16%
12%
8%
4%
0
a
b
c
d
Losses
2.0
4.0
6.0
8.0
10.0
12.0
? ?

FIGURE 3

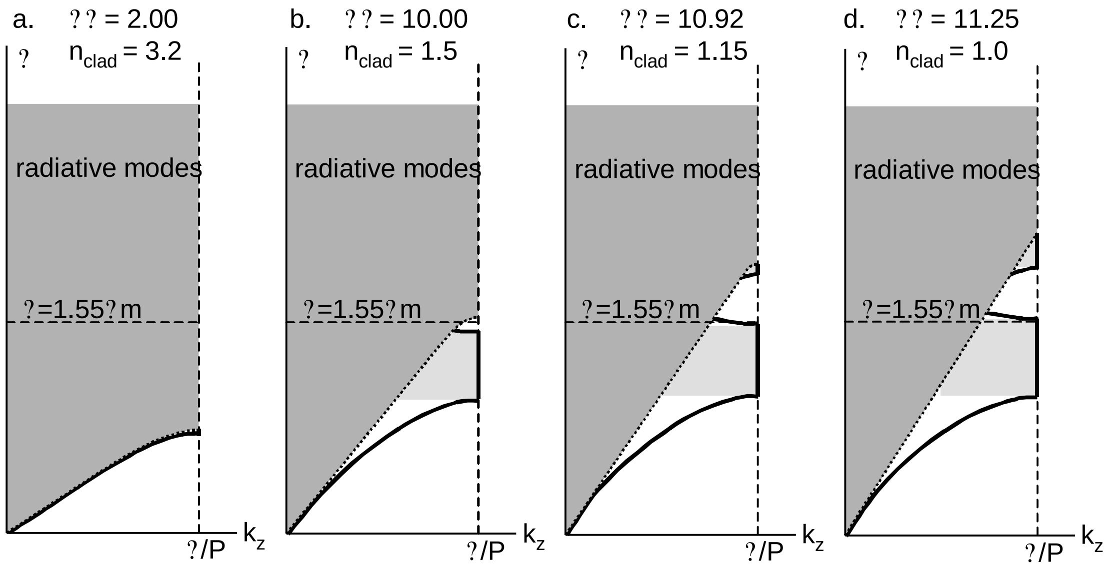
a. ? ? = 2.00
n clad = 3.2
b. ? ? = 10.00
n clad = 1.5
c. ? ? = 10.92
n clad = 1.15
d. ? ? = 11.25
n clad = 1.0
radiative modes
?=1.55?m
?/P
kz

FIGURE 4

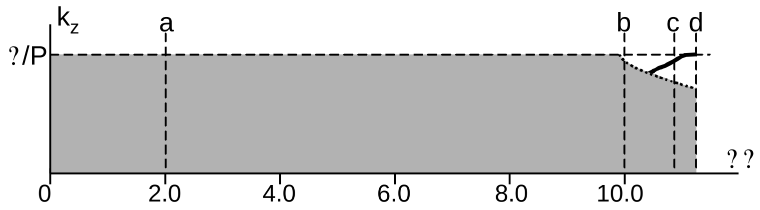

FIGURE 5

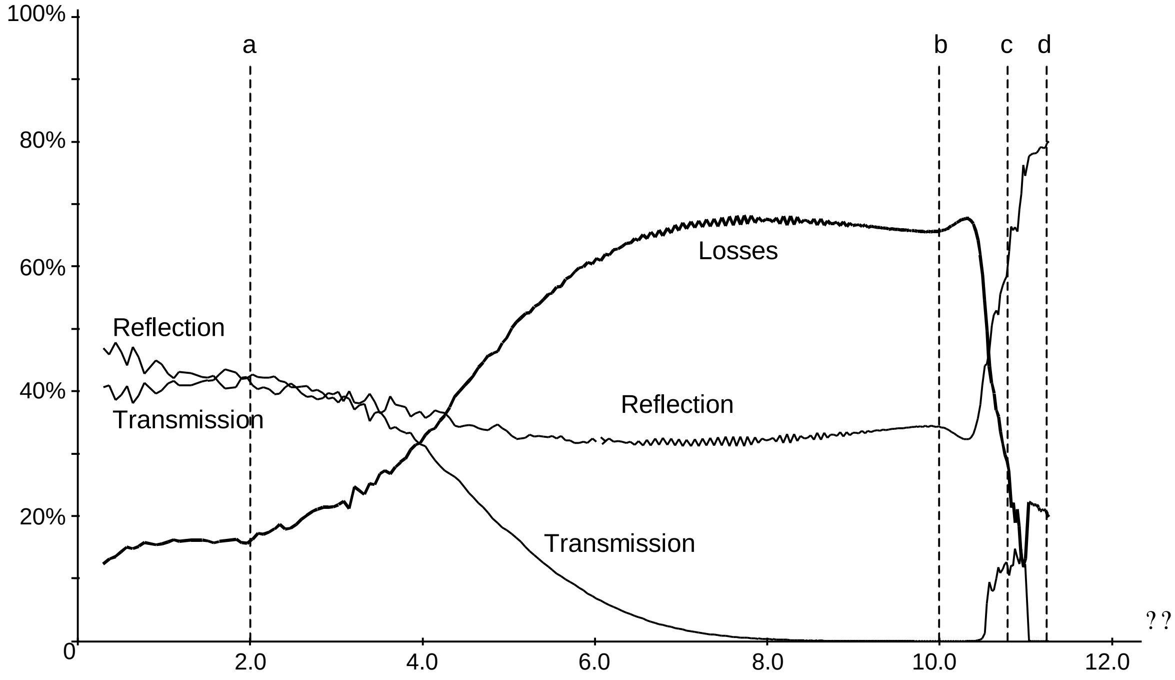
100%
80%
60%
40%
20%
0
a
b
c
d
Losses
Reflection
Transmission
Reflection
Transmission
2.0
4.0
6.0
8.0
10.0
12.0
? ?

FIGURE 6