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Slow-light enhanced absorption in a hollow-core fiber

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Abstract: Light traversing a hollow-core photonic band-gap fiber may experience multiple reflections and thereby a slow-down and enhanced optical path length. This offers a technologically interesting way of increasing the optical absorption of an otherwise weakly absorbing material which can infiltrate the fibre. However, in contrast to structures with a refractive index that varies along the propagation direction, like Bragg stacks, the translationally invariant structures studied here feature an intrinsic trade-off between light slow-down and filling fraction that limits the net absorption enhancement. We quantify the degree of absorption enhancement that can be achieved and its dependence on key material parameters. By treating the absorption and index on equal footing, we demonstrate the existence of an absorption-induced saturation of the group index that itself limits the maximum absorption enhancement that can be achieved.

OCIS codes: (060.5295) Photonic crystal fibers; (060.2310) Fiber optics; (060.2400 Fiber properties; (160.5298) Photonic crystals .

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1. Introduction

Media supporting slow-light propagation of electromagnetic waves are presently receiving tremendous attention in the context of enhanced light-matter interactions. Intuitively, slow-light propagation offers the photons longer time for interacting with the host medium, thus enabling enhanced sensitivity of interferometers and gyroscopes, enhanced non-linear interactions, enhanced spontaneous emission, and enhanced gain and absorption sensitivity, see e.g. [1–7]. Expressing the group velocity as $v_g = c/n_g$, the magnitude of the group index, n_g, relative to that of a reference structure is often taken as a measure of the factor by which slow-light effects enhance light-matter coupling.

A one-dimensional Bragg stack [8] is one example of a structure that can enhance the net absorption experienced by a beam traversing the structure. In this case, the picture of a beam propagation path that is effectively prolonged by multiple back-and-forth scattering in the propagation direction offers a simple physical interpretation. Likewise, photonic crystal structures with immersed liquid have been shown to enhance the absorption, with potential applications in compact lab-on-a-chip implementations of Beer-Lambert-Bouguer absorption measurement schemes [9]. In this latter case, however, the enhancement of the absorption is reduced by a mode filling factor smaller than one that tends to decrease as the mode enters a slow-light regime [9]. Thus, the physical picture offered above for one-dimensional structures has to be modified to take into account that part of the effective propagation path may lie outside the region containing the material with which the interaction is to be increased.

Taking into account this issue of reduced modal overlap it is not immediately clear whether translationally invariant stuctures, which realize slow light effects by a strongly guiding index structure that feature multiple scattering effects in the transverse direction, would offer net absorption enhancement. In this paper we perform a detailed investigation of a recently proposed hollow-core photonic crystal fiber [17] exhibiting a slow-light mode, which is speculated to enhance the effective absorption coefficient of an infiltrated gas. Defining an enhancement

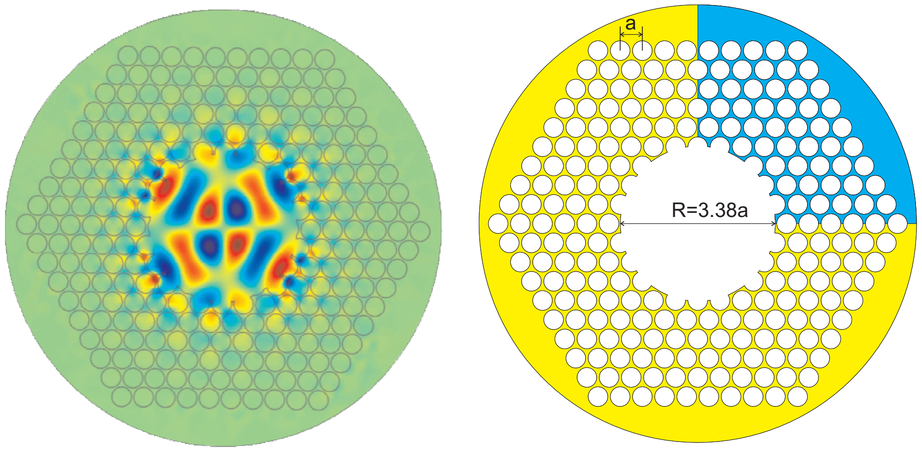

Fig. 1. Left panel shows a typical E_z field pattern for the considered mode,and a right panel shows the fiber geometry with the blue region indicating the symmetry-reduced calculational domain

factor

$$\gamma = \alpha/\alpha_0 \tag{1}$$

where α is the effective absorption coefficient of the fiber, and α_0 is the absorption coefficient experienced by a plane wave propagating through a homogeneously distributed gas, we establish the conditions under which net enhancement can be achieved. From a fully self-consistent solution for the complex propagation constant $\beta(\omega) = \beta'(\omega) + i\beta''(\omega)$, we indeed find a net enhancement factor, that exceeds unity. However, the enhancement factor is significantly smaller than the group index due to the filling factor and, furthermore, we find the important result that absorption itself limits the degree of enhancement that can be achieved.

In this paper we are concerned with slow-light propagation arising from mode dispersion, but slow light effects may also originate from material dispersion, such as electromagnetically induced transparency and coherent population oscillations [6, 7]. However, in these cases the effect of slow-light propagation on the absorption properties are already self-consistently included in the complex susceptibility, and the associated slow-down factor will not directly scale with the intrinsic medium absorption [11].

The paper is organized as follows: In Section 2 we describe the specific photonic crystal hollow core fiber (HCF) considered and the properties of its guided modes. Then, in Section 3, we compute and analyze the dispersion and absorption properties, emphasizing the dependence on the absolute value of the absorption coefficient of the infiltrated gas. Section 4 is devoted to a discussion of the physical interpretation of our results and Section 5 summarizes the conclusions.

2. Slow-light modes in a hollow-core photonic band gap fiber

The particular system we consider belongs to the class of photonic band gap fibers offering hollow-core guidance of optical fields, see e.g. Refs. [13, 14] and references therein. Among many novel properties these fibers are also interesting for studies of light-matter interactions, as the porous structures may be easily infiltrated by e.g. liquids or gasses. Furthermore, the photonic band gap structures offer a tight confinement of the light to the hollow core, thus allowing guidance over long distances and long interaction lengths.

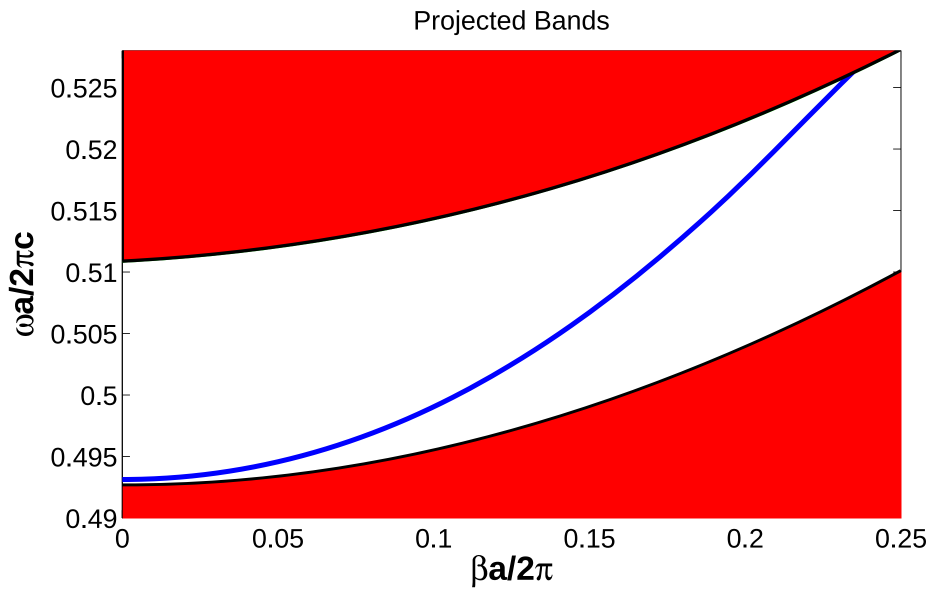

Fig. 2. Dispersion relation (solid curve) for a mode guided in a hollow-core photonic band gap fiber made from a high-index soft glass. The filled regions show the projected bands of the photonic crystal cladding, resulting in a band gap all the way to $\beta = 0$ (white region). Results are obtained for a lossless structure with the wave equation being solved with the aid of a plane-wave method [12].

These fibers are best known for supporting so-called *finger-like* band gaps opening toward high-frequency regimes, even for arbitrary low index contrast [10, 13–15]. However, in silica based hollow-core fibers, the waveguide dispersion does not offer slow light propagation because the index contrast is not sufficiently large to open a band gap that extends all the way down to $\beta = 0$, meaning that there are no slow-light modes. If $v_g = \partial\omega/\partial\beta$ does not change significantly, the effective interaction length is given by the physical length of propagation meaning that absorption would be changed insignificantly. There is a quest for zero-group-velocity modes in longitudinally uniform waveguides [16] and if the index contrast is sufficiently high to support a complete band gap for all polarizations in two dimensions, the projected cladding bands offer a band extending all the way down to $\beta = 0$. Turning to soft glasses with a higher dielectric function than silica, theoretical predictions show possibilities for this [17]. The translational invariance of course implies inversion symmetry, so any guided mode will be symmetric with respect to $\beta = 0$. For the ideal lossless fiber we have $\beta = \beta'$ and the dispersion relation is a real analytic function, thus implying that

$$\omega(\beta) = \omega_0 + \frac{1}{2}\left(\frac{\partial^2\omega}{\partial\beta^2}\right)_{\beta=0}\beta^2 + \mathscr{O}(\beta^4), \quad (\beta'' \to 0) \tag{2}$$

and the group velocity is consequently zero when approaching small values of wave numbers. Such a mode has been recently proposed for slow-light enhanced absorption [17], which could be interesting in the context of previous studies of gases infiltrated in hollow-core fibers [18,19]. The right panel of Fig. 1 shows the hollow core fibre geometry and the left panel displays a mode profile for the E_z component, while Fig. 2 illustrates a dispersion relation for a confined mode. In reality, however, the confinement loss associated with a photonic crystal cladding of

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finite extension will cause β to be complex. The dispersion relation may then no longer have the simple parabolic dependence near $\beta = 0$ and the group index $n_g = c\partial\beta'/\partial\omega$ will saturate rather than diverge.

Infiltrating the fiber with a weakly absorbing gas is expected to further promote the saturation of the group index, as shown recently in the case of photonic crystals and photonic crystal waveguide structures [20, 21]. Obviously, the apparent absorption-induced saturation of the group index n_g will have consequences for the group-index enhanced absorption [22]. In the following we numerically study this interplay for the hollow-core fiber proposed in Ref. [17].

3. Numerical analysis

The fiber geometry we consider is illustrated in the right panel of Fig. 1. For the soft glass material, we use a dielectric function $\varepsilon = n^2 = (2.7)^2 = 7.29$ and the photonic crystal cladding has a triangular lattice of air-holes. During fiber drawing the air-holes will tend to become hexagonal with rounded corners [23], but for simplicity we consider circular air-holes with diameter $d = 0.9\,a$, where a is the lattice constant. The hollow core is formed by introducing an air defect with a radius $R = 3.38\,a$ in the otherwise periodic structure. With this choice of defect radius, the guided mode is well confined to the hollow core and the air-light overlap is fairly high. In our simulations, the cladding structure comprises 7 rings of air holes, which causes a sufficiently low leakage loss as compared to the absorption properties of the gas that we are considering. For fewer rings of air holes, there is a stronger saturation of the group index even in absence of the additional saturation caused by gas absorption itself.

We employ a commercially available finite-element method (Comsol Multiphysics) to solve the wave equation

$$\left[\nabla_t^2 + \varepsilon(x,y)\left(\frac{\omega}{c}\right)^2 + \left(\frac{\nabla_t^2\varepsilon(x,y)}{\varepsilon(x,y)}\right)\times\nabla_t\times\right]H_t(x,y) = \beta^2 H_t(x,y) \tag{3}$$

for the transverse magnetic field $H_t(x,y)$. Adaptive meshing is used to ensure an efficient convergence and efficient use of spatial grid points. Rather than writing the wave equation as an eigenvalue problem, with ω^2 being the eigenvalue, we have here rewritten it as an eigenvalue problem for β^2 which is then solved for a fixed frequency, which physically corresponds to an excitation by a well determined frequency. We emphasize that the strength of this method is to allow a direct calculation of the complex propagation constant along with the possibility to also account for dispersive materials. In this paper, for simplicity, we neglect such material dispersion.

The calculation domain is truncated with the aid of perfectly-matched layers, which allows us to also include the effects of leakage loss due to the finite spatial extension of the photonic crystal cladding. Leakage loss manifests itself as a small imaginary part β'' of the effective propagation constant, even in the absence of any material absorption. The dispersion results of Fig. 2 for the ideal lossless structure are used as an initial guess for the finite-element solution, in order to track the mode in the ω versus β space more easily. Likewise, the symmetry of the mode shown in the left panel of Fig. 1 is also enforced, which reduces the computational domain to one fourth of its original size; and also significantly eases tracking of the desired mode. In reducing the computational domain, care must be taken that the imposed boundary conditions along the symmetry directions respect the hybrid nature of the mode, in most cases implying in total 6 boundary conditions associated with electric and magnetic field components.

Figure 3 summarizes our results for the complex dispersion relation in the presence of leakage loss and a possible additional absorption due to the infiltration of the hollow core by a weakly absorbing gas. For the gas, we consider a complex refractive index $n = n' + in'' = 1 + in''$, with the imaginary part ranging from 0.001 to 0.01. The left panel shows the dispersion

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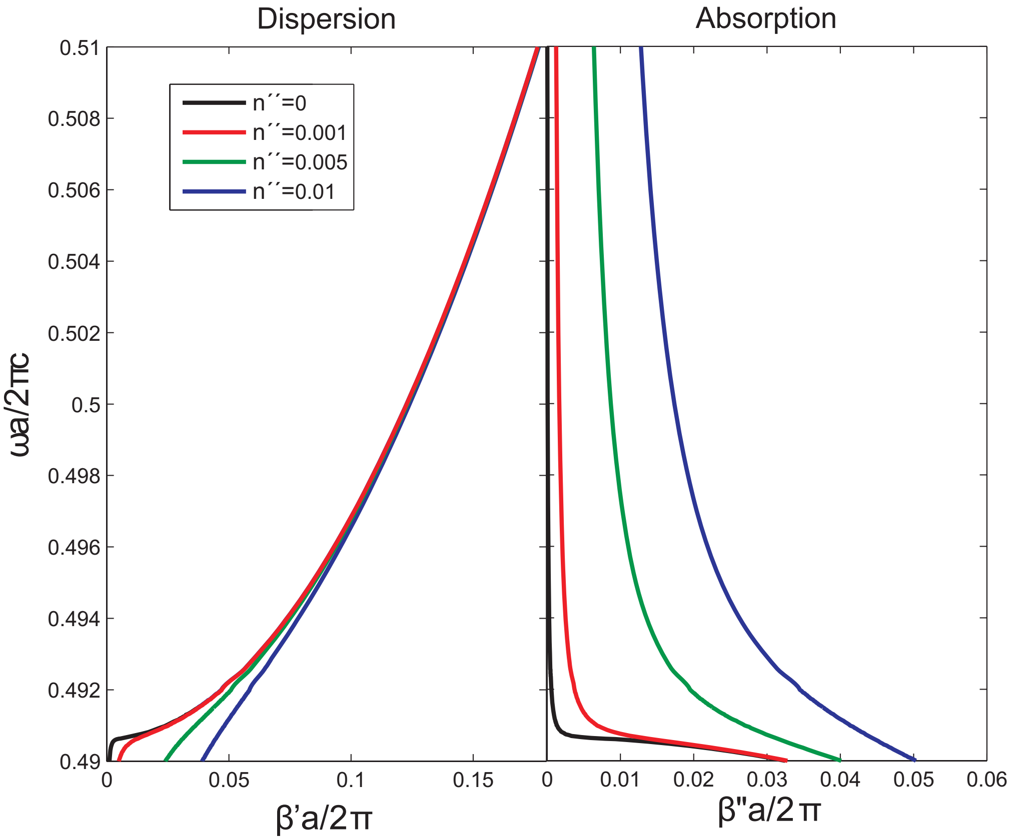

Fig. 3. Complex dispersion relation for the hollow core fiber being infiltrated by an absorbing gas with $n = n' + in''$ with $n' = 1$ and n'' ranging from 0 to 0.01. The left panel shows the dispersion while the right panel shows the corresponding absorption in dependence of the frequency (vertical axis).

relation, i.e. ω versus β', while the right panel shows the corresponding damping, i.e. ω versus β''. As clearly seen, the dispersion departs significantly from the ideal lossless case shown in Fig. 2 in the assumed slow-light regime near $\beta' = 0$. Rather than approaching ω_0 with a small slope, the dispersion relation turns very steep near $\beta' \sim 0$. However, we emphasize that this apparent super-luminal group velocity is accompanied by strong damping, as seen in the right panel.

Our focus is to explore to which extent a low group velocity will enhance light matter interactions. Figure 4 shows the corresponding absorption enhancement factor γ along with the group index n_g. In order to correct Eq. (1) for the radiation-induced damping we use $\gamma \equiv 2\left[\beta'' - \beta''(\alpha_0 \to 0)\right]/\alpha_0$. The bending of the dispersion curve discussed above manifests itself in a saturation of the group index as compared to a diverging group index for the ideal lossless structure (right panel). However, despite the saturation of the group index, the absorption may still be enhanced (left panel).The effect of broadening of the electromagnetical modes causes a smearing of the density of states (DOS) and a removal of the singular behavior. This has its counterpart in the group index, which remains finite so that the group velocity is limited by n'' [21]. This is in particular true for the lowest values of n'', where the saturation of the

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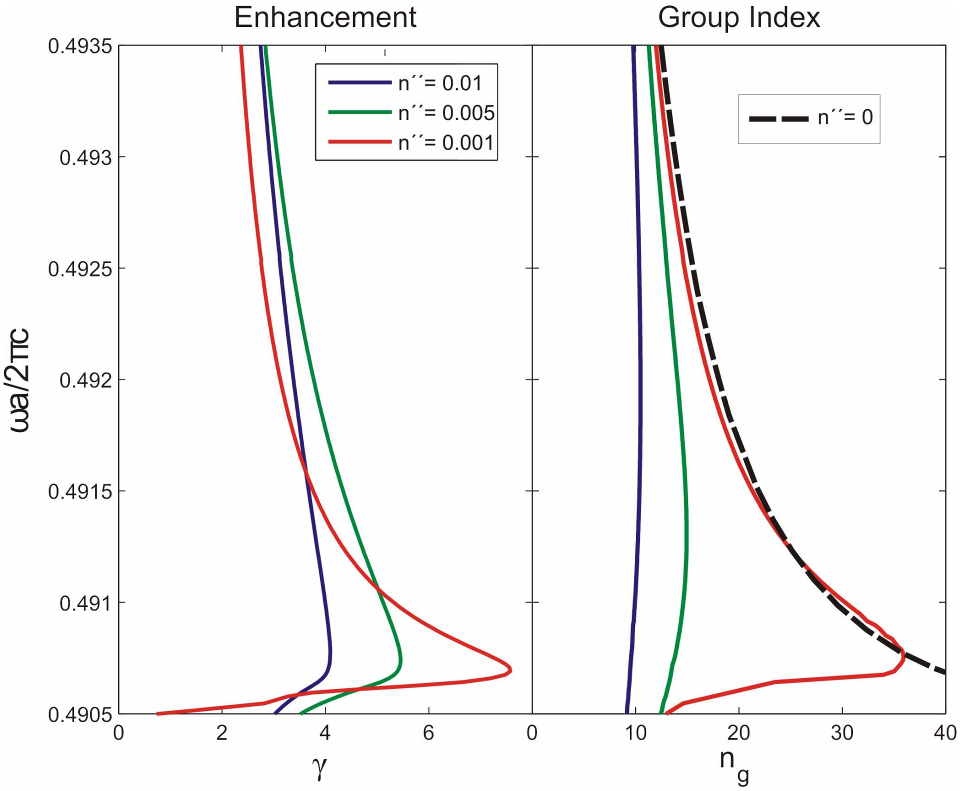

Fig. 4. Comparison of the absorption enhancement factor (left panel) and the group index (right panel), both derived from the results in Fig. 3. For the absorbing gas, n'' is varied in the range from 0.001 to 0.01. In the right panel, for comparison the dashed line represents the group index in the ideal structure, neglecting both leakage loss and absorption (calculated with the aid of a plane-wave method as in Ref. [17]).

group index is less pronounced. However, stronger gas absorption jeopardizes the group index, and a strong slow-light enhancement is absent. In Ref. [9] it was, by means of perturbation theory, predicted that $\gamma \propto n_g$. While this expression neglects the additional saturation of the group index itself due to absorption, the fully self-consistent solution still confirms the trend, as seen by the correlation between a high group index in the right panel and a high absorption enhancement in the left panel. It is thus evident that the exploitation of a slow light mode enables the enhancement of the net absorption experienced by a beam traversing the structure as compared to the beam traversing a homogeneous medium. We emphasize, that the weaker the intrinsic absorption of the gas is, the larger the absorption enhancement that can be achieved by exploiting the slow-light dispersion relation of the hollow-core fiber. For sensing applications this is particularly interesting since it allows sensing gas substances in the very dilute regime and thus highly dispersive hollow-core fibers potentially constitute an interesting platform for development of such gas sensing devices.

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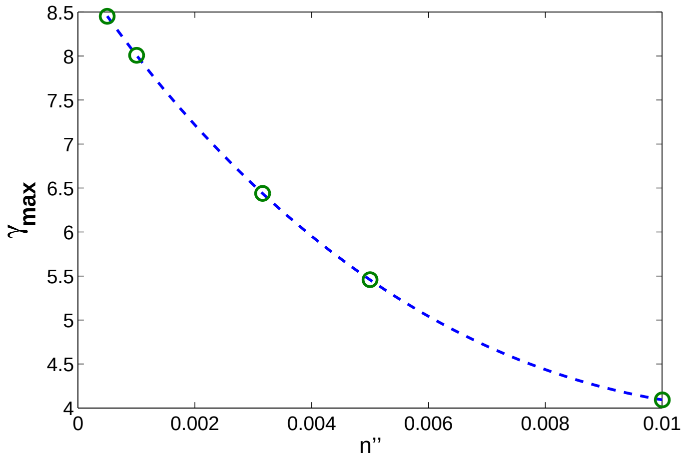

Fig. 5. The maximal absorption enhancement factor γ_{max} versus intrinsic gas absorption n'' for the infiltrated gas.

Figure 5 summarizes how the maximum enhancement factor is influenced by intrinsic absorption of the gas. As discussed above, the enhancement factor increases in the dilute gas limit, where the intrinsic absorption of the gas becomes lower.

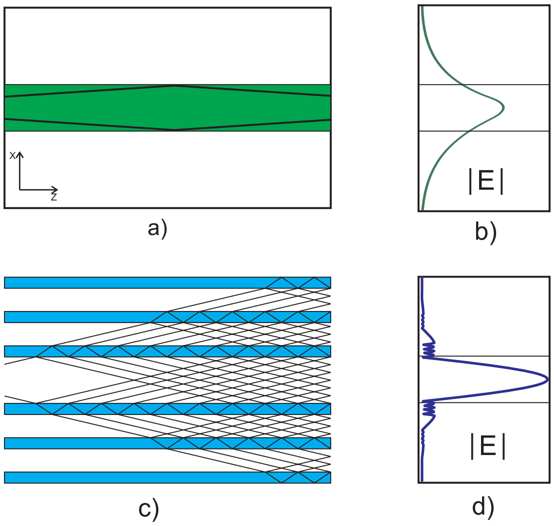

Fig. 6. Schematic illustration of light rays for a) index-guided and c) band-gap guided modes. b) and d) show the corresponding field confinement profiles. Very small inclination of wave vector with respect to the interface in the dielectric slab, panel a), implies a very weak field confinement, panel b). The multiple reflections in a 2D translationally invariant guide with transversal periodicity, panel c), may cause a more tight field confinement, panel d).

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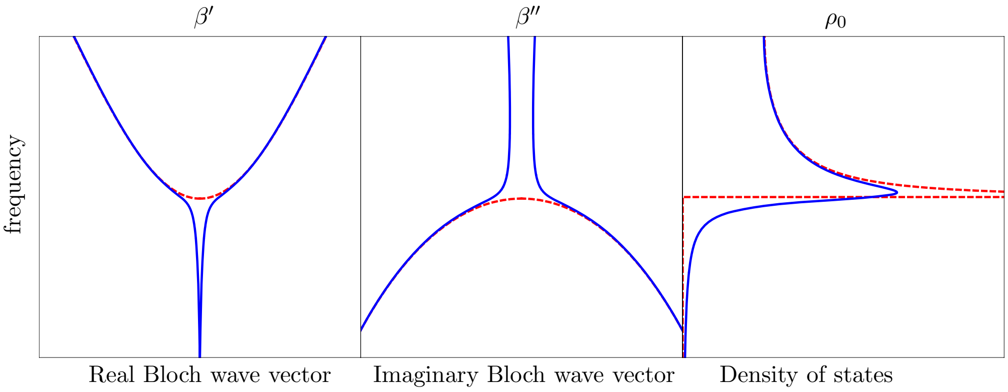

Fig. 7. Schematic illustration of complex dispersion relation.The dashed lines mimic the lossless case while the solid lines are in the presence of moderate damping in the system. Left panel illustrates the real part of the dispersion relation; middle panel represents the imaginary part. The right panel shows the: shows the associated DOS illustrating, how the van Hove singularity is smeared in the presence of damping

4. Discussion

Here we would like to illustrate our ideas with two very simple examples. In the first example we show how the periodic structure may play a significant role in the field confinement that is one of the important ingredients in order to have enhanced absorption. The second example shows changes in the complex dispersion relation induced by a small imaginary part of the dielectric constant.

The waveguide dispersion of weakly guided modes can be shown not to support enhanced absorption. Due to the fact that the confinement factor is small, benefits of a slowly propagating pulse are offset. The confinement factor measures the fraction of the electric field energy concentrated in the core region with respect to the total electric energy in the structure. In Fig. 6(a) we show a weakly guiding dielectric slab where the corresponding geometrical rays are almost parallel to the interface, resulting in the electric field being weakly confined in the structure, see Fig. 6(b). The confinement factor can be made larger by making the waveguide wider, but not without jeopardizing the slow-light propagation supported by the wave guide dispersion. More formally, if we derive the weakly guiding propagation equation no slow-light enhancement occurs [11]. Figure 6(c) illustrates a contrasting case where multiple scattering from a periodic Bragg structure serves to strongly confine the mode in the core, see Fig. 6(d), while at the same time supporting a longer effective propagation path.

In Fig. 7 we schematically illustrate the effects of the imaginary part of the refractive index on the complex dispersion relation and density of states. The group velocity v_g goes to zero near the band edge in the lossless case (red dotted lines), while losses (blue lines) introduce a bending that leaves v_g finite. Likewise, the middle panel shows how the attenuation turns finite also inside the band. Below the cut-off of the band ($\omega < \omega_0$), the lossless case corresponds to purely imaginary values for β and the mode is not propagating in this frequency region. In the right panel, the loss manifests itself as a smearing of the van Hove singularity in the DOS. In conclusion, in the presence of absorption, v_g will be significantly modified in the $\beta' = 0$ region. We emphasize that the apparent superluminal behavior associated with the very steep part of curve of course is accompanied by a pronounced damping as seen from the middle panel.

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5. Conclusion

We have analyzed the possibility for slow-light enhanced absorption in translationally invariant waveguides with strong confinement and waveguide dispersion. As a particular example we have shown how hollow-core photonic band gap fibers may potentially be used for enhanced absorption measurements in the context of detection of dilute and weakly absorbing gasses. Our work offers an important example of the possibility of enhanced absorption due to slow-light waveguide dispersion, even in translationally invariant structures, thus confirming expectations based on perturbation analysis. Our results also illustrate the importance of treating the issues of absorption and group index on an equal footing and in a fully self-consistent way: while a high group index promotes enhanced absorption the absorption serves to saturate the group index.

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