Elimination of the band gap of a resonant optical material by electromagnetically induced transparency

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We consider the possibility of wave propagation in the normally disallowed (band-gap) region of a resonant optical medium, that is, in the band of frequencies near resonance where the real part of the frequency-dependent dielectric function is negative. We demonstrate that wave propagation can become allowed by the application of a strong electromagnetic field resonant with some additional transition of the material system. The frequencies at which these effects can occur are strongly influenced by local-field effects.

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It is well known [1] that electromagnetic waves with wave vector \( \vec{k} \) cannot propagate in the frequency region where the dielectric function \( \epsilon(\omega) \) of the medium is negative. This conclusion follows from the standard dispersion relation \( k^2 = (\omega^2/c^2) \epsilon(\omega) \). By way of illustration, let us consider a material system characterized by a dielectric function of the form

\[
\epsilon(\omega) = \epsilon_0 \left( 1 + \frac{\omega_p^2 - \omega_0^2}{\omega_0^2 - \omega^2} \right),
\]

Here \( \epsilon_0 \) is the background dielectric constant, \( \omega_p \) is a parameter [defined by \( \epsilon(\omega_p) = 0 \)] that characterizes the strength of the optical response, and we ignore the effects of damping. We see from Eq. (1) that \( \epsilon(\omega) \) is negative in the frequency region \( \omega_0 < \omega < \omega_p \). This region corresponds to a band gap—a region in which only evanescent waves are possible. This band gap occurs even though in our model \( \epsilon(\omega_p) \) is a real quantity. It is also known that the optical properties of a medium can be modified significantly by the application of resonant electromagnetic fields. In particular, resonant absorption can be made very small by the application of a control field leading to electromagnetically induced transparency (EIT) [2–5]. The question thus arises: Is it possible to eliminate the band-gap region of a resonant optical material by the application of electromagnetic fields? We examine this question in detail and produce an answer in the affirmative. We examine a model system that is of relevance in many applications and that could be generalized easily in several ways depending on need. We take full account of local-field effects [6–9] because band gaps can occur only in dense systems. We demonstrate that such a band gap can occur in alkali-metal vapors and can be removed by the application of a strong control field, although because of self-broadening effects alkali-metal vapors are not an ideal system for studying such effects.

It should be noted that the situation considered here is very different from those under which EIT has been previously studied. EIT is usually used to minimize absorption at frequencies for which \( \text{Re} \epsilon(\omega) \) is large. In contrast, we consider the possibility of allowing propagation at frequencies where \( \text{Re} \epsilon(\omega) \) is small but where propagation is usually prevented by the fact that \( \text{Im} \epsilon(\omega) \) is negative. We also note that earlier Harris [10] showed how the application of an additional electromagnetic field can produce propagation at a frequency below the cutoff frequency in an ideal plasma. Harris utilized collective effects arising from nonlinearities in a plasma to produce EIT in plasma. In our work local-field effects play an important role—these effects arise from dipole-dipole interactions and are in a sense like collective effects. We note still further that Scully and co-workers [11] have produced schemes based on quantum interferences for the enhancement of the refractive index of a medium. In their work the region of interest is \( \text{Re} \epsilon > 0, \text{Im} \epsilon = 0 \). We note that in Zibrov et al.’s case [11] the susceptibility can take negative values but \( \epsilon \) is still positive.

Let us now consider a more detailed theoretical model based on the coupling scheme shown in the inset of Fig. 1. We consider first the optical response to a single applied field at frequency \( \omega_0 \); we will later see how this response is modified by the application of an additional control field of frequency \( \omega_c \). The linear response at frequency \( \omega \) is given by the standard “two-level” model as [12].

\[
\chi = \frac{n|\tilde{d}_{13}|^2}{\hbar(\Delta - i\Gamma)}, \quad \Delta = \omega_{13} - \omega.
\]

Here, as usual, \( n \) is the atomic number density of the medium, \( \tilde{d}_{13} \) is the transition dipole matrix element, and \( \Gamma \) is the half width at half maximum of the transition \( |1\rangle \leftrightarrow |3\rangle \). The susceptibility as modified by local-field effects is given in Gaussian units by

\[
\chi_i = \frac{\chi}{1 - \frac{4\pi}{3} \chi}.
\]