Slow Electromagnetic Waves and Resonance Phenomena in Photonic Crystals

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The problem of slowing down electromagnetic (EM) waves has been extensively discussed in the literature. Such a possibility can be useful in a variety of microwave and optical applications. Our objective is to compare different ways to achieve this effect in linear dispersive media such as photonic crystals. A very low group velocity $v_g = \partial\omega/\partial k$ corresponds to stationary points of the dispersion relation $\omega(k)$. In periodic layered media, the dispersion relations can develop only three kinds of stationary points. Assuming that the values ω_s and k_s correspond to a stationary point, the above three possibilities can be defined as follows

1. The vicinity of a band edge, where $\omega - \omega_s \sim (k - k_s)^2$
2. The vicinity of a stationary inflection point, where $\omega - \omega_s \sim (k - k_s)^3$.
3. The vicinity of a degenerate band edge, where $\omega - \omega_s \sim (k - k_s)^4$.

The case 1 relates to a common EM band edge, it can be found in any periodic array. By contrast, the cases 2 and 3 can only occur in periodic arrays with special geometry [1-6]. In all three cases the group velocity v_g vanishes as ω approaches ω_s. But when the efficiency of conversion of incident light into the slow mode is concerned, the three cases are fundamentally different from one other. Consider plane EM wave incident on semi-infinite photonic crystal with dispersion relation having a stationary point at $\omega = \omega_s$. What happens if the wave frequency ω approaches ω_s? Let S be the energy flux associated with the slow wave transmitted inside the crystal. It turns out that in the vicinity of photonic band edge (case 1), the energy flux S of the transmitted wave vanishes along with the group velocity $v_g = \partial\omega/\partial k$. This implies total reflection of the incident wave as $\omega \to \omega_s$.

By contrast, in the vicinity of stationary inflection point (case 2), the energy flux $\boldsymbol{S}$ remains finite even at $\omega = \omega_s$, contrary to the fact that the wave group velocity vanishes. The latter implies that the wave amplitude inside the photonic crystal increases dramatically. In steady-state regime, the incident wave with $\omega = \omega_s$, after entering the periodic structure, gets almost 100% converted into a non-Bloch frozen mode with the energy density growing quadratically with the distance from the photonic crystal boundary. Thus, the case 2 provides ideal conditions for slowing down the EM wave by a semi-infinite photonic crystal.

Finally, in the vicinity of degenerate band edge (case 3), the energy flux $\boldsymbol{S}$ vanishes, similarly to what we had in the vicinity of a regular band edge (case 1). At the same time, the electromagnetic energy density inside the periodic structure now becomes enormous, similarly to what takes place in the vicinity of stationary inflection point (case 2).

Finite bounded periodic structures supporting the frozen mode regime, can also display a giant Fabry-Perot cavity resonance associated with the degenerate photonic band edge [6]. In contrast to the regular transmission band edge resonance, in the case of degenerate band edge the field intensity enhancement is proportional to the forth degree of the number of layers in the stack. This allows to drastically reduce the dimensions of the resonant cavity without compromising on performance. This effect can be realized not only in bounded photonic crystals, but also in a waveguide environment, as well as in a finite array of coupled resonators.

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