Electromagnetic propagation in a relativistic electron gas at finite temperatures

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The knowledge of the responses of a relativistic electron gas (REG) at finite temperatures and densities to electromagnetic (EM) radiation is a useful tool for understanding the physics of several systems, as in condensed matter physics as also astrophysical scenarios. Investigations of the response of a REG to the action of an external electromagnetic perturbation have many similarities with studies in the fields of photonics and plasmonics, where it is crucial to understand the propagation of EM and plasmonic modes that are also present in the REG. In photonics and plasmonics one normally uses phenomenological expressions for the responses of the media of interest. Here, however, one may actually compute such responses from first-principles, so that we envisage applying our techniques in the future to the actual computation of the responses of artificially constructed materials. Using quantum electrodynamics at finite temperatures, we describe electromagnetic propagation in a REG at finite temperatures and carrier densities and obtain electric and magnetic responses and general constitutive relations. Rewriting the propagator for the electromagnetic field in terms of the electric and magnetic responses, we identify the modes that propagate in the gas. As expected, we obtain the usual collective excitations, i.e., a longitudinal electric and two transverse magnetic plasmonic modes. In addition, we find a purely photonic mode that satisfies the wave equation in vacuum, for which the electron gas is transparent. We present dispersion relations for the plasmon modes at zero and finite temperatures and identify the intervals of frequency and wavelength where both electric and magnetic responses are simultaneously negative, a behavior previously thought not to occur in natural systems.