Drifting Electrons: Nonreciprocal Plasmonics and Thermal Photonics

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Reciprocity limits the performance of thermal photonic systems by enforcing a symmetry between absorption and emission processes. Specifically, emissivity and absorptivity are equal according to Kirchhoff's law of thermal radiation. Rather surprisingly, however, this law is not a requirement of the second law of thermodynamics, but it originates directly from Lorentz reciprocity. Another consequence of reciprocity in this context is that the radiative heat flux density becomes symmetric for opposite in-plane wavenumbers, both in far-field and near-field heat transfer. Interestingly, it has been demonstrated that breaking reciprocity is necessary to achieve certain thermodynamic limits in radiative thermal energy harvesting and photonic heat engines. Unfortunately, however, there are only few options to achieve nonreciprocal thermal platforms. Standard nonreciprocal materials, e.g., gyrotropic magneto-optical materials, or more exotic media, such as Weyl semimetals, suffer from the need of external magnets or weak nonreciprocal response in the mid-infrared frequency range, whereas nonreciprocal platforms based on space-time modulations are difficult to scale to the optical frequency range.

Here, we focus on another approach to break reciprocity either in three-dimensional (3D) systems (metals, semiconductors, and plasmas) or two-dimensional (2D) materials such as graphene. This method is based on driving a DC electric current through the structure with sufficiently high drift velocity v_d to affect the dispersion of surface plasmon-polaritons (SPPs). The effect of drifting electrons on SPPs propagation can be explained in an intuitive way: SPPs are collective charge oscillations coupled to light, hence they are either dragged or opposed by the drifting electrons, which causes surface modes to see different media when propagating along or against the current. The origin of this nonreciprocal behavior is rooted in the frequency Doppler shift due to the electron drift velocity, $\omega \to \omega - \mathbf{k} \bullet \mathbf{v}_d$. This method has received some attention in the context of plasmonic waveguiding, but, to the best of our knowledge, it has not yet been applied to thermal photonics.

In this work, we employ this method to break reciprocity in 3D plasmonic platforms with particular focus on nonreciprocal thermal radiation. We found that driving the system with an electric current determines different regimes of SPPs propagation. The presence of drifting electrons opens a frequency window where, for any in-plane direction, a frequency can be found at which the SPPs propagate as steerable, unidirectional, collimated beams. Away from this frequency, SPPs spread due to diffraction, but the unidirectionality is still preserved. Such a rich nonreciprocal plasmonic behavior can be used to achieve asymmetric near-field heat transfer. Specifically, we employed this approach in the context of near-field 3D radiative heat transfer between two planar bodies. We identified a signature of nonreciprocity by showing that the presence of drifting electrons leads to an asymmetry in the heat flux density. This means heat gets transferred from body 1 to body 2 in one channel while the opposite transfer occurs through a different channel, and this asymmetry results in a heat current loop between the two bodies even when they are kept at the same temperature, as recently discussed in different papers based on magneto-optical materials. Our findings might open uncharted directions in developing nonreciprocal, miniaturized, integrated, thermal photonic devices which do not rely on external magnets to manage the heat flow at the micro- and nano-scale.