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Dedication lecture

KIRCHHOFF'S LAW OF THERMAL RADIATION: THE ORIGIN, GENERALIZATION, AND NEW INTERPRETATIONS

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In his landmark paper on the relation between the emissive power and absorptivity (Ann Physik, vol. 109, pp. 275-301, 1860), Gustav Kirchhoff envisioned that an enclosure at thermal equilibrium behaves as a blackbody (perfect absorber). Furthermore, he argued that for a given polarization, the ratio of the radiant power emitted by an object (per unit area per unit wavelength interval) to its spectral directional absorptivity is a function of the wavelength and temperature only. Because the absorptivity of a blackbody is one, its emissive power is a universal function of wavelength and temperature. Further experimental and theoretical investigations by Josef Stefan, Ludwig Boltzmann, Wilhelm Wien, Otto Lummer, and Max Planck in the late nineteenth century led to the establishment of the laws of blackbody radiation, especially Planck's law in 1900.

It should be noted that, based on his experimental studies and theoretical arguments involving thermal equilibrium, Balfour Stewart made a statement in 1858, a couple of years prior to Kirchhoff's paper, that the absorption of a plate equals its radiation for every *description* (which could be interpreted as color or wavelength) of heat. Kirchhoff's approach was clearly more rigorous and quantitative. The contemporary expression of Kirchhoff's law is the equality between the spectral directional absorptivity and emissivity in counter-parallel directions, for which Kirchhoff derived under the Helmholtz reciprocity proposition (also known as the Lorentz reciprocity nowadays). For materials with magneto-optic effect or with internal magnetization, the Lorentz reciprocity may break down, resulting in nonreciprocal thermal emission.

Magneto-optic and magnetic materials have recently been explored by many researchers to control thermal emission and absorption characteristics for energy harvesting and thermal management. These materials often exhibit chirality and can be used to obtain circularly polarized thermal emission. Kirchhoff's law has been reformulated or generalized to nonreciprocal materials under thermal equilibrium. Fluctuational electrodynamics allows a direct calculation of thermal emission of an object for arbitrary polarization states described by Stokes parameters, which can be expressed in terms of polarized emissivities for partially polarized emissions. On the other hand, the indirect method calculates Fresnel's coefficient matrix consisting of both co- and cross-polarization terms. Understanding the relationships between the quantities obtained from the direct and indirect approaches is critical to the proper interpretation of generalized Kirchhoff's law. Current research trend in nonreciprocal and circularly polarized emission will be highlighted.