Kirchhoff's laws of thermal radiation for complex, nonreciprocal, and time-varying materials

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Kirchhoff's law of thermal radiation states that the angle and frequency resolved absorptivity and emissivity of an object are equal. In recent years, metamaterials have demonstrated large control over the absorptivity and emissivity [1,2], in some cases requiring extensions of Kirchhoff's law. For example, Kirchhoff's law has recently been extended to structures where the emitted polarizations are correlated [3]. We verify this extension experimentally by demonstrating a direct measurement of the absorptivity and emissivity of a metasurface emitting circularly polarized light, which confirms that the emissivity is the complex conjugate of the absorptivity. Using a nonreciprocal coupled-mode theory we developed [4], we then discuss an extension of Kirchhoff's law to nonreciprocal materials, which shows i) equivalence between absorption in an object and emission from its time-reversed counterpart and ii) that passive, nonreciprocal emitters always satisfy the second law of thermodynamics. Finally, we investigate thermal radiation from time-varying materials. We present a Kirchhoff's law of thermal radiation, which readily enables calculation of the emission through knowledge of the absorption, which often is much easier to obtain, and demonstrate some systems where the standard Kirchhoff's law is violated in unique ways.

References

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