Large Non-reciprocity and Isolation with Time-Varying Zero-Index Electrical or Acoustical Channels

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Reciprocity is a fundamental property of classical wave phenomena both in electromagnetics and acoustics, and it is a direct consequence of the symmetry of wave propagation under time reversal. Following this general fact, Onsager showed in 1931 that reciprocity can be broken through biasing with any physical quantity that is odd-symmetric under time reversal. To date, magnetic biasing has been the prevailing method for obtaining non-reciprocity, but other quantities that satisfy the general requirements of Onsager's principle, such as linear and angular momentum, have recently attracted significant attention as promising alternatives. Momentum can be realized either mechanically, as in an acoustical ring cavity filled with a rotating medium, or electrically, as in a spatiotemporally modulated optical waveguide. Spatiotemporal modulation has been successfully applied to realize one-way waveguides, however, the existing designs involving a non-uniform modulation profile across the waveguide cross-section significantly complicate fabrication and practically limit the performance. In addition, the requirements on modulation frequency and amplitude may be large, restricting operation to low frequencies and the level of practically achievable isolation.

Here, we combine the principle of linear momentum biasing with the unique tunneling phenomena in zero-index waveguides, designing electrical and acoustical one-way waveguides with strong transmission asymmetry, yet without the problems of previous designs. Tunneling through an INZ channel is the result of impedance matching between the feeding waveguides and the INZ channel, and it occurs when the INZ channel's cross-section is much smaller that the waveguide's cross-section. Such impedance matching is made possible by the strong dispersion of the INZ impedance, which becomes infinite or zero at the INZ frequency. A very important property of INZ tunneling is that it involves travelling waves, contrary to standing waves in resonant coupling through Fabry-Perot cavities. As a result, by imparting a physical or effective motion to the INZ channel, it is possible to shift the INZ frequency by different amounts for opposite propagation directions and realize a system where tunneling through impedance matching is possible only in one direction. Our analysis shows that fairly small values for the physical or effective velocity of the channel is enough to produce strong non-reciprocity, as a result of the large sensitivity of the channel impedance to changes in the INZ frequency. Furthermore, when motion is effectively realized through spatiotemporal modulation, a small number of discrete modulation regions are sufficient to create a strong effect, due to the almost uniform phase distribution along the INZ channel.