The Positive and Negative Goos-Hänchen Shifts with Left-handed Slabs

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A generalized analytic formulation for analyzing the Goos-Hänchen (GH) lateral shift direction is provided, from which we show that the phenomenon of both positive and negative GH shifts at different incident angles can be observed with left-handed material (LHM) slabs. The formulation also reveals that this unique phenomenon is related to the relative amplitudes of the evanescent waves inside the LHM slabs, which is confirmed by the study of energy flux patterns.

By introducing the analytical equation for the GH shift direction

$$sign\{S\} = sign\left\{-\frac{\mu_{1r}}{\mu_{2r}}\,[C - C_1][C - C_2]\right\} \tag{1}$$

where C is ratio of the growing and decaying evanescent wave amplitudes inside the slab, while C_1 and C_2 are functions of slabs parameters and the beam's incident angle, we are able to analyze the GH shift direction change and its dependence on the incident angles and the slab's thickness. Although the well-known equation $S = -\left.\partial\Phi(k_x)/\partial k_x\right|_{k_x=k_{ix}}$ can also be used for the parametric study of GH shifts, Eq. 1 has the advantage of directly relating GH shift directions to the slab's parameters and the electromagnetic waves in the system. More importantly, the physical meaning of the value of C is the ratio of the growing and decaying evanescent wave amplitudes inside the slab. Hence Eq. 1 reveals the connections between the GH lateral shift direction change and the variations of the ratio of the evanescent wave amplitudes inside the slab.

It can be shown that the existence of a *simultaneous* positive and negative GH shift at different angles is due to the fact that the GH shifts can change directions as the LHM slab thickness becomes smaller. The changes of GH shift directions at different slab thicknesses can be understood intuitively. For a very thin LHM slab (relative to the wavelength), the presence of the slab has little effect on the waves and the total internal reflections are mainly due to the third medium resulting in positive GH shifts. For an electrically thick LHM slab, however, the total internal reflections are mainly due to the LHM slab, yielding a negative GH shift. In between these two extremes, there exist a certain slab thickness in which *simultaneous* positive and negative shifts occur. In addition, a unique property of the LHM slab is that depending on the constitutive parameters, a slab can be electrically thick but still yield a positive GH shift as if the slab were electrically thin. As an extreme example, when the LHM slab is exactly matched to the third medium, the GH shift is always positive regardless of the slab thickness. The physical reason for this effect is related to the energy flux pattern inside the slab, which is also addressed.