Longitudinal and transverse effects of nonspecular reflection

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A rigorous spectral analysis is given for the nonspecular reflection of a three-dimensional Gaussian beam at a dielectric isotropic planar structure. For the first time all independent nonspecular effects are derived in a self-consistent manner for the three-dimensional case. It is shown that the longitudinal nonspecular effects in the incidence plane, that is, the lateral and focal shifts of the beam waist position, the angular rotation of the reflected-beam axis, and the modifications of the beam waist width and complex amplitude, have their direct analogies in the plane transverse to the incidence and interface planes that gives transverse nonspecular effects. Moreover, the existence of the other, not yet reported, effect of nonspecular modification of the beam polarization is also proved. A role for TM and TE polarizations in reflected-beam formation is indicated. The results show that, up to the symmetric second-order terms in approximation of Fresnel coefficients, each of the longitudinal and transverse beam factors independently preserves its shape under reflection at the expense of changes of the beam reference frame, width, amplitude, and polarization parameters.

1. INTRODUCTION

The nonspecular theory of reflection spectacularly displays potential abilities of the aberrationless approach widely used in analysis of several (propagation, diffraction, scattering and interaction) phenomena in linear and nonlinear optics. Within the aberrationless approach the optical field is supposed to have a specified, usually Gaussian, shape, and the process under consideration is described by changes of a few parameters characteristic of the presumed field *Ansatz*. Such an approach implies a conversion of a partial differential equation guiding the process (such as the linear or nonlinear Schrödinger equation) into a set of ordinary differential equations. The set of ordinary differential equations describes, through the changes of the beam parameters, the dynamics of the process and provides a clear and simple interpretation of the beam interaction. A good example of such an approach is the well-known[1–3] paraxial aberrationless analysis of self-focusing or self-defocusing phenomena in nonlinear Kerr dielectric media.

The nonspecular theory of reflection or transmission concerns a problem of the beam interaction with, in general, a multilayered structure, rather than propagation in a homogeneous medium. The field dynamics is governed by Helmholtz or Schrödinger equations, which are mutually linked through the paraxial approximation[4] and translated into Fresnel coefficients at interfaces of medium discontinuities. For Gaussian incidence the reflected or transmitted field is assumed also to be of the (nonspecularly deformed) Gaussian form. In the evaluation of the beam deformations under reflection or transmission the reference beam is understood as the geometric-optical (g-o) beam reflected at the structure or transmitted through it, according to geometrical optics predictions. The beam deformations are described by changes of parameters of the g-o Gaussian beam.

For the three-dimensional (3-D or 2 + 1) case analyzed in this paper there are 20 parameters that completely describe the (fundamental) Gaussian beam. Two of them specify a location of the beam waist in lateral and focal directions, transverse and parallel to the beam propagation direction, respectively. The next two determine the direction, i.e., the propagation angle, of the beam propagation and the beam waist width. These four parameters create a set of geometrical parameters of the beam, as they determine the beam geometry. Actually, there are 16 geometrical parameters, four for both TM and TE beam polarization, separately measured in the incidence and transverse (to the incidence and interface planes), mutually orthogonal planes. Besides geometrical parameters, there are four parameters describing magnitude and phase of the on-axis beam complex amplitude for both TM and TE polarization states. The reflected or transmitted beam is described by the nonspecular changes of these parameters with respect to the reflected or transmitted g-o beam. Therefore, that should give a complete set of 20 independent nonspecular effects of the beam interaction with the structure.

The nonspecular reflection phenomenon was predicted in 1929 by Picht[5] in his studies on energy flux inside evanescent waves caused by total internal reflection. The first reported nonspecular effect—the longitudinal (in the incidence plane) lateral beam displacement, known as the Goos–Hänchen shift—was experimentally observed in 1947 by Goos and Hänchen.[6] Analytical expressions for this shift were given by Artmann[7] in 1948, on the grounds of a stationary-phase approach, and by Fragstein[8] in 1949, who used energy-flux conservation principles. For a detailed overview of early studies on nonspecular reflection the reader is referred to papers by Lotsch.[9] Up to now, only longitudinal effects known in the two-dimensional (2-D or 1 + 1), i.e., scalar, case have been explored in a self-consistent manner, that is, in a

