Two-slab all-optical spring

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It is demonstrated that a waveguide consisting of two dielectric slabs may become an all-optical spring when guiding a superposition of two transverse evanescent modes. Both slabs are transversely trapped in stable equilibrium due to the optical forces developed. A condition for stable equilibrium on the wavenumbers of the two modes is expressed analytically. The spring constant characterizing the system is shown to have a maximal value as a function of the equilibrium distance between the slabs and their width. © 2007 Optical Society of America

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Electromagnetic forces on neutral bodies may prove to be the foundation of a variety of future optomechanical systems. In addition to the vast research devoted to the manipulation of small particles by laser light,¹ one of the subjects that have been investigated is the trapping of a mirror in a stable equilibrium state by using radiation pressure. A typical configuration is that of a Fabry–Perot cavity consisting of two mirrors, where the radiation pressure on one of the mirrors may be balanced by an external mechanical force.²,³ This scheme has been recently experimentally characterized as an optical spring.⁴–⁷

In contrast to the Fabry–Perot system where radiation is incident perpendicularly upon each mirror, waveguide eigenmodes propagate in the longitudinal direction while exerting pressure on the guiding structure in the transverse direction.⁵–⁶ It was recently shown that two mirrors guiding light between them may experience both attractive and repulsive forces according to the transverse behavior of the mode they guide.⁷ In fact, transverse propagating modes, namely, eigenmodes with real transverse wavenumbers, were found to always be repulsive. On the other hand, transverse evanescent modes may be repulsive or attractive, depending on whether their transverse fields are odd or even functions of the transverse coordinate, respectively.

When both an attractive and a repulsive mode are propagating in a two-mirror waveguide, the total transverse force may trap each mirror in a stable equilibrium state. To some extent, this effect resembles the optical binding of dielectric particles by scattered laser light.⁹ Since only optical forces are responsible for the equilibrium, we may consider the system an all-optical spring. Such a stable equilibrium has been demonstrated for a waveguide consisting of two Bragg mirrors.⁷ Although the diverse properties of Bragg mirrors may be exploited for controlling the radiation pressure in a two-mirror waveguide,⁵,⁷ for the realization of an all-optical spring, Bragg reflection may not be necessary. Instead, the two transverse evanescent modes that are required may be guided by total internal reflection.

In this Letter the optical forces in a two-slab system consisting of two infinite lossless dielectric slabs, as illustrated in Fig. 1, are investigated. By using a total internal reflection mechanism, the transverse oscillations of the field in the Bragg reflector are avoided, and the radiation pressure effects for a given power are enhanced. It is demonstrated for the first time to our knowledge that this configuration may become an all-optical spring, and a general analytic expression for the condition for stable equilibrium to occur is developed, as well as an expression for the spring constant. In addition to the obvious advantage in implementation, the simplicity of the system allows us to gain insight into the stable equilibrium phenomenon.

Derivation of the dispersion relations in the two-slab system illustrated in Fig. 1 may be found in Ref. 10, and recently the propagation of light in this type of nano-waveguide was demonstrated.¹¹ In what follows, we focus on the lowest even TM mode (Eₘ is even) and the lowest odd TE mode (Hₘ is odd); both are assumed to be at wavelength λ₀ with corresponding angular frequency ω₀ = 2πc/λ₀, propagating in the z direction. Obviously, in a practical device that has a finite size in the y direction, the modes are hybrid rather than being pure TE or TM. However, the larger this dimension is, the more accurate the present analysis becomes.

For each mode, the Maxwell stress tensor¹² is used to compute the force per unit area per unit power (Nm⁻²W⁻¹) F_A and F_R for the attractive TM and for the repulsive TE, respectively; negative values of the force represent attraction, whereas positive values represent repulsion. Figure 2 shows contours of the two normalized forces as a function of the distance between the slabs D and the slabs’ width Δ, for slabs of permittivity εᵣ = 3.45² ≈ 11.9. The normalization is by (cλ₀Δ)⁻¹, where Δ is the width in the y direction through which the power flows. It is seen that the

Fig. 1. Two-slab waveguide. H_z for the odd TE mode is superimposed on the schematic of the system.