Controlling the repulsive Casimir force with the optical Kerr effect

C. H. Raymond Ooi* and Y. Y. Khoo

Department of Physics, University of Malaya, 50603 Kuala Lumpur, Malaysia

(Received 4 September 2012; revised manuscript received 22 October 2012; published 17 December 2012)

The Casimir force between two plates can be controlled using combinations of dispersive metamaterials and nonlinear materials with the optical Kerr effect. The force can be significantly varied and switched between positive and negative values by changing the intensity of a laser pulse. The switching sensitivity increases for small separation between the plates, providing new possibilities of integrating optical devices into nanoelectromechanical systems.

DOI: 10.1103/PhysRevA.86.062509 PACS number(s): 31.30.jh, 12.20.−m, 03.70.+k, 03.65.−w

I. INTRODUCTION

The presence of the physical boundaries in a quantized electromagnetic field leads to changes in the vacuum energy level and may be observed as a vacuum force. This effect was first postulated and theoretically derived by Casimir [1]. Since then, efforts have been made to investigate the Casimir force for various geometries and boundary conditions [2–5]. Various corrections to the ideal cases, including temperature corrections, have been considered [6–8]. However, in most cases the force is found to be attractive [9].

With microelectromechanical systems (MEMS) and nanoelectromechanical systems (NEMS) becoming increasingly complex, scaling issues had become the center of attention. Scaling NEMS systems downward will inevitably bring up the issue of Casimir interaction between metallic and dielectric surfaces in close proximity, such as stiction [10–12]. This problem may be avoided if the Casimir force is repulsive [9,13]. Therefore, repulsive Casimir force had received renewed interest [14–16].

Recent advancement in the synthesis of artificial materials with magnetic properties $|\mu| > 1$ has led to new possibilities for controllable electromagnetic properties. These metamaterials may have either negative permittivity ε or permeability μ (single-negative materials) [17,18] or simultaneously negative permittivity ε and permeability μ [19] over a band of frequency (left-handed materials [LHM's]) [20–24]. Casimir forces involving metamaterials are of particular interest, as they may be repulsive. In particular, the possibilities of quantum levitation of an ultrathin conductor have been investigated by having a LHM lens sandwiched between two perfectly conducting plates [25]. Casimir force between LHM plates has also been investigated [26–28]. Furthermore, it is also possible to control the Casimir force by adjusting the frequency-dependent electromagnetic properties of materials [9].

In this paper, we study the Casimir force between metamaterial plates driven by an external high-intensity laser source which introduces the optical Kerr effect (OKE) on the plates. This is a nonlinear optical effect due to the third-order polarization in the presence of a strong laser field. Although the OKE is well-known in nonlinear optics and intense laser propagation [29], it has not been utilized to manipulate the properties of the quantum vacuum. Recent work involving the magneto-optical Kerr effect involves polarization of light [30] instead of a strong laser field. We show that it is possible to gain control of the sign and magnitude of the Casimir force, thus providing optical controllability over the Casimir force between plates. Particular interest is focused on the repulsive force by introducing artificial magnetic permeability realized with metamaterials.

In Sec. II, we provide the Lifshitz theory that gives an integral expression for the Casimir force for parallel plates with arbitrary magnetic permeability and dielectric permittivity. Section III describes how the OKE affects the force for parallel plates composed of i) a purely magnetic or dielectric plate and a perfectly reflecting plate, (ii) a metamaterial plate and perfectly reflecting plate, or (iii) a piecewise-dispersive model for ε and μ in one plate and a perfectly reflecting plate. In Sec. IV, we elaborate on realistic linear and nonlinear responses that include dispersion and absorption of a metamaterial plate and a nonlinear Kerr material plate that produce a strong intensity-dependent Casimir force. The results are summarized in Sec. V.

II. BASIC THEORY

Based on the stress tensor method, the Casimir force between two parallel, infinite plates A and B, separated by a distance a in free space, may be expressed as [31,32]

$$
\begin{aligned}
F_c(a) = & -\frac{\hbar}{\pi}\mathrm{Re}\int_0^\infty d\omega \iint \frac{d^2k}{(2\pi)^2}\sqrt{\frac{\omega^2}{c^2}-k^2} \\
& \times \sum_{p=\mathrm{TE,TM}} \frac{r_p^A(\omega,k)r_p^B(\omega,k)e^{i2a\sqrt{\omega^2/c^2-k^2}}}{1-r_p^A(\omega,k)r_p^B(\omega,k)e^{i2a\sqrt{\omega^2/c^2-k^2}}} \\
= & \frac{\hbar}{2\pi^2}\int_0^\infty d\xi \int_0^\infty kdk\sqrt{\frac{\xi^2}{c^2}+k^2} \\
& \times \sum_{p=\mathrm{TE,TM}} \frac{r_p^A(\xi,k)r_p^B(\xi,k)e^{-2a\sqrt{\xi^2/c^2+k^2}}}{1-r_p^A(\xi,k)r_p^B(\xi,k)e^{-2a\sqrt{\xi^2/c^2+k^2}}}, \qquad (1)
\end{aligned}
$$

where k is the (tangential) component of the wave vector parallel to the plate surface, ξ is the imaginary frequency where $\omega = i\xi$, and r_p^j is the slab's reflection coefficient for transverse electric (TE) and transverse magnetic (TM) polarized waves. The positive (negative) sign of F_c corresponds to attractive (repulsive) force.

*rooi@um.edu.my

We then consider the effect of semi-infinitely thick parallel plates with respect to transmission of virtual photons, which reduces the slab's reflection coefficient to the single interface reflection coefficients [9]:

$$r_{\rm TE}^{j}=\frac{\mu_j\sqrt{\xi^2/c^2+k^2}-n_j\sqrt{\xi^2/c^2+k^2/n_j^2}}{\mu_j\sqrt{\xi^2/c^2+k^2}+n_j\sqrt{\xi^2/c^2+k^2/n_j^2}},$$
$$r_{\rm TM}^{j}=\frac{\varepsilon_j\sqrt{\xi^2/c^2+k^2}-n_j\sqrt{\xi^2/c^2+k^2/n_j^2}}{\varepsilon_j\sqrt{\xi^2/c^2+k^2}+n_j\sqrt{\xi^2/c^2+k^2/n_j^2}}, \tag{2}$$

where $n_j=\sqrt{\varepsilon_j\mu_j}$ is the index of refraction for plate $j=A,B$. It is noted that the Casimir force in Eq. (1) can be negative (repulsive) only if the reflectivity of both plates A and B differs in sign. This may occur only if both plates have very different electromagnetic properties across some resonances. A thorough treatment was done to investigate the changes in the Casimir force due to changes in electromagnetic properties of the respective plates [9]. It was noted that if two plates have the same electromagnetic properties in the lower-frequency region and opposite electromagnetic properties in the higher-frequency region, the Casimir force would vary from repulsive to attractive as the distance between plates increases [9]. Conversely, if two plates have opposite electromagnetic properties in the lower-frequency region and similar electromagnetic properties in the higher-frequency region, the Casimir force would vary from attractive to repulsive as the distance between plates increases [9].

III. INTENSITY-DEPENDENT CASIMIR FORCE

To allow optical control of the Casimir force, a laser beam of intensity $I(\omega)$ is introduced to induce the OKE on both plates. The effective index of refraction is then given by

$$n_j(\omega)=\sqrt{\varepsilon_j(\omega)\mu_j(\omega)}+\eta_{2,j}(\omega)I(\omega), \tag{3}$$

where $\eta_{2,j}$ is the coefficient of the Kerr effect and $I(\omega)=If(\omega)$, which indicates that the spectral shape $f(\omega)$ of the laser pulse may also determine the ultimate dispersion of $n_j(\omega)$.

From Eq. (2), we notice that the magnitude of the refractive index may determine the sign of the reflectivity by competing with the first term in the numerator. In turn, the Casimir force between plates may be controlled by $I(\omega)$. For a broadband pulse spanning over the resonant frequency of $\eta_2(\omega)$, its intensity can be taken to be constant. It is interesting that the Casimir force may become time dependent if the OKE is induced by a time-dependent laser pulse. The study of the transient effect in the Casimir force requires a different approach, i.e., in time domain; this is beyond the present formalism.

In an effort to understand the Casimir force, we consider an idealized magnetic plate driven by the intense laser field where $\varepsilon_A=1$, $\mu_A=5$, η_2 is finite, placed parallel to a perfectly conducting plate [$r_{\rm TE}^B=-1, r_{\rm TM}^B=1$ (when Re $\varepsilon_B\gg 1$), $\eta_2=0$] that can be realized. In Fig. 1(a), we have plotted the Casimir force F_c between the plates as a function of intensity of the impinging laser, for interplate distance $a=0.1\lambda_0$. Here the wavelength in vacuum is $\lambda_0=2\pi c/\omega_0=10^{-6}$ m, with $\omega_0=2\pi c\times 10^6$ s^{-1}, and Casimir forces are expressed in terms of $K=hc/(64\pi^3\lambda_0^4)\simeq 10^{-3}$ Nm^{-2}(energy density, J m^{-3} or pressure, Nm^{-2}).

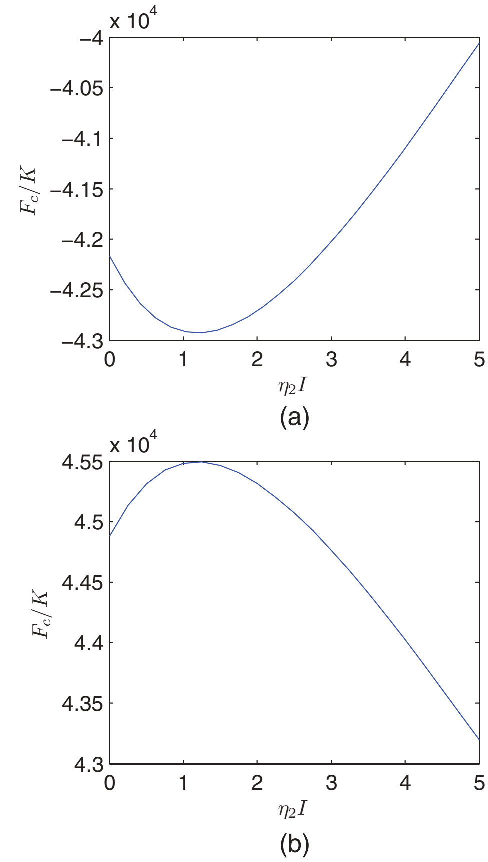

FIG. 1. (Color online) Casimir force between a perfect conductor ($r_{\rm TE}^B=-1, r_{\rm TM}^B=1$) and a plate with (a) $\varepsilon=1,\mu=5$, and (b) $\varepsilon=5$, $\mu=1$, as a function of intensity of impinging laser $\eta_2(\omega)I$. Interplate separation is $a=0.1\lambda_0$.

The first plate is mainly magnetic, and we find the Casimir force to be *repulsive* for any laser intensity. However, with a laser intensity of about $\eta_2 I\approx 1$, we noticed an optimum repulsive force. The slight increase in the magnitude of the force is caused by the TM reflectivity which decreases quicker compared to the TE reflectivity. At higher intensities, the Casimir force between plates becomes less repulsive.

A similar curve is plotted in Fig. 1(b), with the first plate being substituted with $\varepsilon_A=5$, $\mu_A=1$. Notice that the *attractive* force between the plates increases slightly when $\eta_2 I\approx 1$, corresponding to a quicker onset in $r_{\rm TE}$ compared to $r_{\rm TM}$. We therefore notice that for $\varepsilon>\mu$ ($\varepsilon<\mu$), $r_{\rm TE}$ ($r_{\rm TM}$) decreases more quickly compared to $r_{\rm TM}$ ($r_{\rm TE}$), giving a small increase in magnitude on the original attractive (repulsive) Casimir force. At higher intensities, the Casimir force between plates become less attractive (repulsive).

When one of the plates is a metamaterial and the other is a metal, the force is entirely repulsive for any spacing a and intensity, as seen in Fig. 2. However, the Casimir force is sensitive to the laser intensity only at small intensity and small interplate spacing.

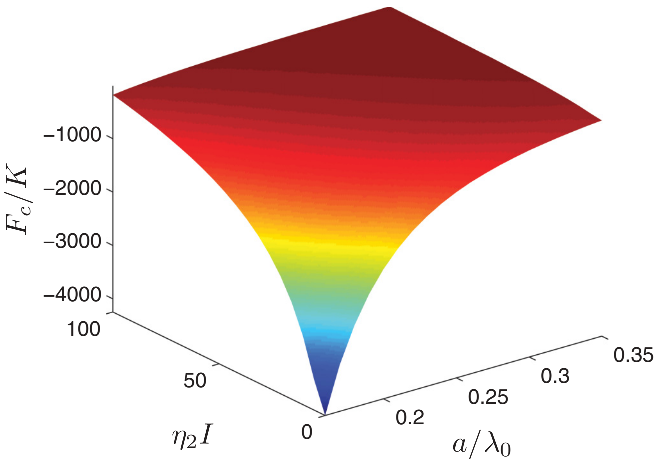

FIG. 2. (Color online) Casimir force between a perfectly conducting plate and a metamaterial with $\varepsilon = 1$, and μ modeled by Eq. (5) with parameters of $\omega_{P_m} = 3\omega_0$, $\omega_{T_m} = 2\omega_0$, and $\gamma_m = 10^{-2}\omega_{T_m}$.

In order to demonstrate the possibility of laser control of the Casimir force, we take an ideal, piecewise-dispersive material with material constants given by

$$\varepsilon = \begin{cases} 10, & \omega < \omega_T, \\ 1, & \omega \geqslant \omega_T, \end{cases} \qquad \mu = \begin{cases} 0.5, & \omega < \omega_T, \\ 100, & \omega \geqslant \omega_T. \end{cases} \tag{4}$$

This material is noted to be mainly magnetic at high frequency, while being electric at low frequency, and can be influenced by the Kerr effect. The Casimir force between this plate and a perfectly conducting plate, which will not be influenced by the OKE ($r_{\rm TE} = -1$, $r_{\rm TM} = 1$, $\eta_2 = 0$), is plotted in Fig. 3(a) for $\omega_T = 0.8\omega_0$. It is noted that the Casimir force is negative and depends most sensitively on intensity at short distances. In Fig. 3(b), we have plotted the dependence of the Casimir force on laser intensity for different distances between plates. It is noted that an increase in laser intensity to $\eta_2 I \approx 40$ is sufficient to change the Casimir force from attractive to repulsive, for $a \approx 0.2\lambda_0$. Thus, by introducing materials with piecewise dispersion, nonlinear response to laser field, such as the OKE, can be used to tailor the transient variations of the force magnitude and even the sign.

IV. COMPLEX LINEAR AND NONLINEAR COEFFICIENTS

In this section, we consider the Casimir force for practical materials with actual dispersion (and absorption) taken into consideration. We let one of the plates be a Kerr material and the other plate be a metamaterial. Since the Casimir effect is a broadband response it must be integrated over all frequencies. Thus we must take into account the dispersion and absorption in the dielectric permittivity ε and magnetic permeability μ such that the real and imaginary parts of the complex refractive index obey the Kramers-Kronig relation and does not violate causality. Similarly, the nonlinear Kerr coefficient η_2 is complex and depends on frequency ω.

For the metamaterial plate, we use the complex linear response functions modeled by a Drude-Lorentz type of single

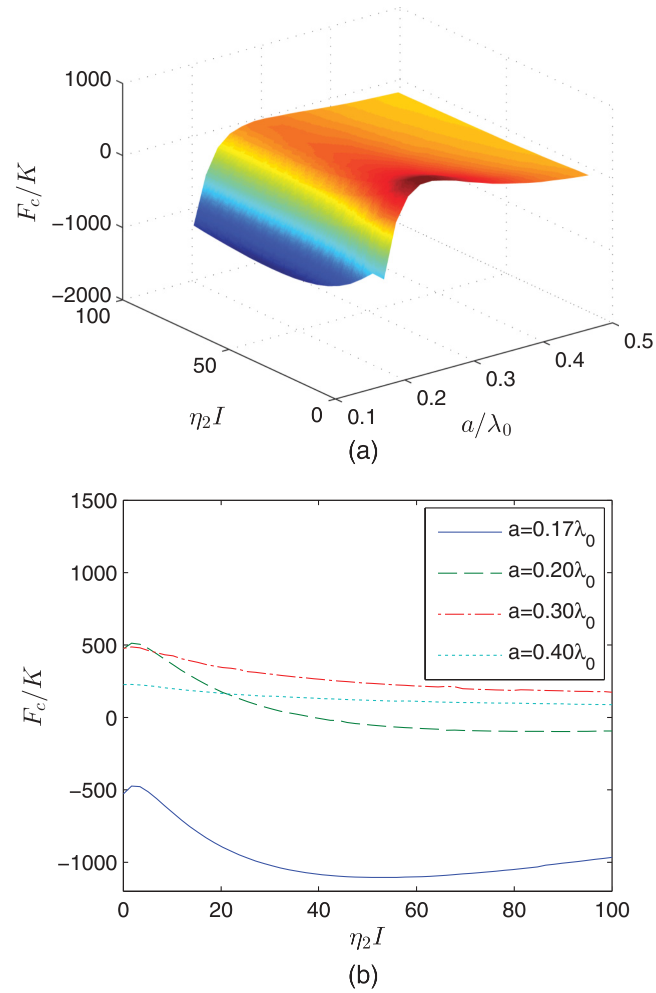

FIG. 3. (Color online) Casimir force F_c between a perfect conducting plate and a piecewise-dispersive dielectric-magnetic plate of Eq. (4), as a function of separation between the plates and laser intensity. (a) 3D plot and (b) curves for different specific spacings.

resonance,

$$\{\varepsilon,\mu\} = 1 + \frac{\omega_{P_v}^2}{\omega_{T_v}^2 - \omega^2 - i\gamma_v\omega}, \quad \eta_2 = 0, \tag{5}$$

where $v = e,m$ refers to ε and μ, respectively, while $\omega_{P_v}^2$, $\omega_{T_v}^2$, and γ_v are the plasma frequency, the resonance frequency, and the damping frequency, respectively. The metamaterial is modeled using Eq. (5) with parameters $\omega_{P_e} = 0.5\omega_0$, $\omega_{T_e} = 10^{-3}\omega_0$, $\omega_{P_m} = 3\omega_0$, $\omega_{T_m} = 2\omega_0$, and $\gamma_{e(m)} = 10^{-2}\omega_{T_{e(m)}}$.

The Kerr material is chosen to be a chalcogenide glass, As_2Se_3, due to its high nonlinear refractive index. The linear refractive index n_0 of the glass with dispersion is modeled using the Wemple equation [33] based on a single electronic oscillator model,

$$n_0^2(\omega) - 1 = \frac{E_d E_s}{E_s^2 - (\hbar\omega)^2 - i\hbar^2\omega\gamma}, \tag{6}$$

where E_s is the Sellmeier gap and E_d is the electronic oscillator energy. For As_2Se_3, $E_s = 4.1$ eV, while $E_d \approx 26$ eV for many chalcogenides [34]. We take the damping factor,

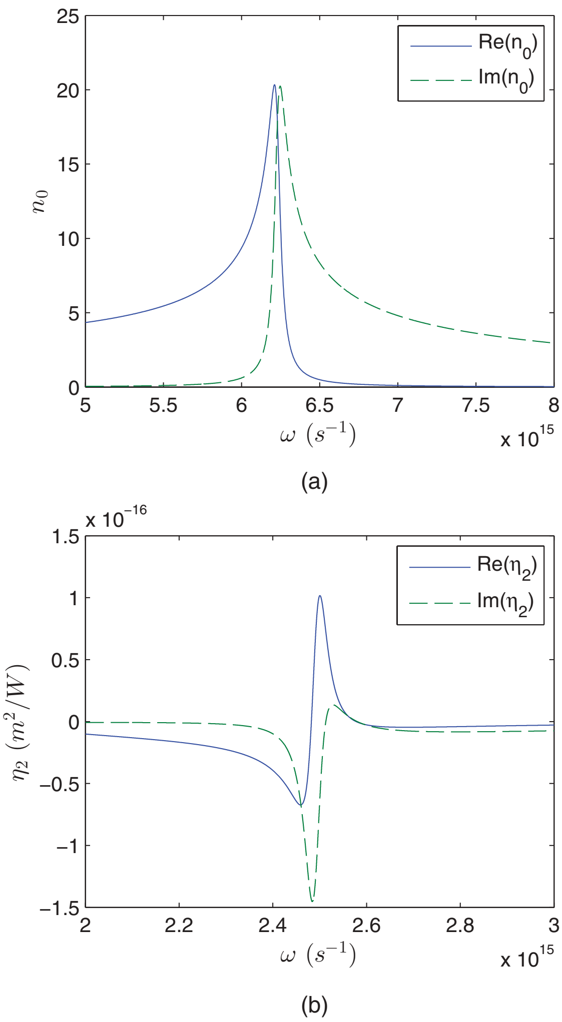

FIG. 4. (Color online) (a) n_0 of As_2Se_3 as modeled using the Wemple equation. (b) η_2 of As_2Se_3 as modeled using Eq. (7).

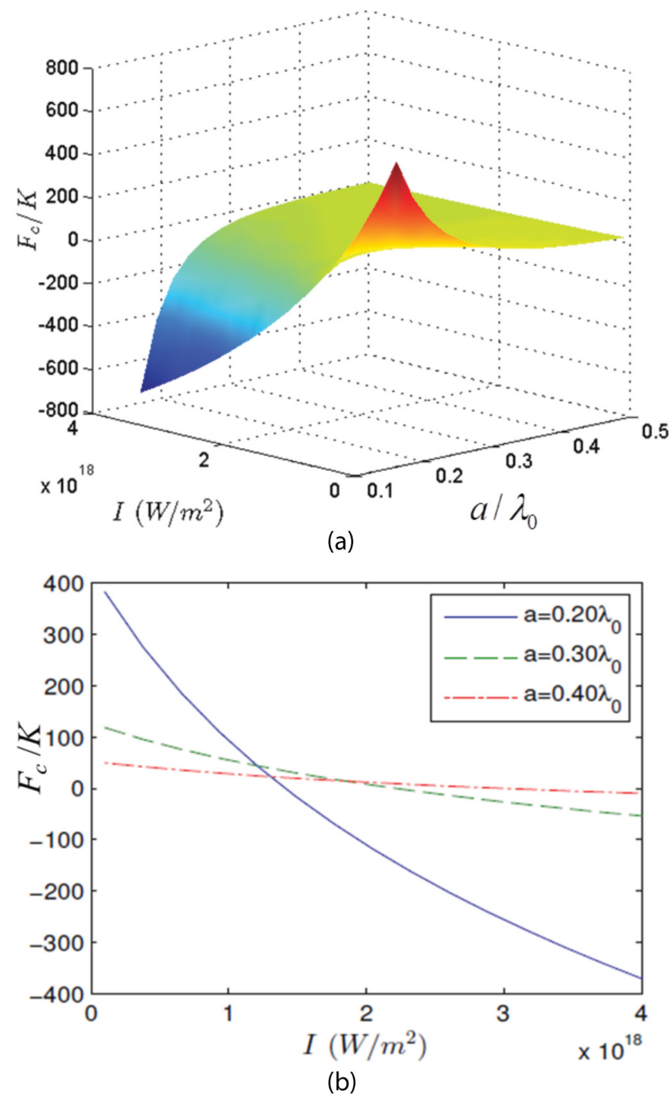

FIG. 5. (Color online) Casimir force F_c between an As_2Se_3 plate and a metamaterial with complex permeability and permittivity given in Eq. (5) as a function of separation between plate and intensity of laser.

$\gamma = 10^{-2}E_s/\hbar$. The dispersion and absorption of n_0 are plotted in Fig. 4(a).

The complex nonlinear refractive index η_2 is modeled using the theory by Lenz *et al.* [35],

$$\eta_2(\omega) = C\left(n_0^2+2\right)^3\left(n_0^2-1\right)\left(\frac{d}{n_0 E_s}\right)^2 G\left(\frac{\hbar(\omega+i\gamma)}{E_g}\right), \tag{7}$$

where $C = 1.7\times10^{-18}$, d is the mean anion-cation bond length of the bonds that are primarily responsible for the nonlinear response (in units of nanometers), and E_g is the optical gap. For As_2Se_3, $d = 0.243$ nm [34]. It is noteworthy that $E_s \sim 2.5E_g$ [34], which gives $E_g = 1.64$ eV. The dispersion of the Kerr coefficient is contained in the function G, which may be estimated with a two-band model. The expressions for $G(x)$, as given in the Appendix, include contributions from two photon absorption, the Raman effect, the linear Stark effect, and the quadratic Stark effect [36]. The dispersion and absorption of η_2 is plotted in Fig. 4(b).

Using the complex expressions of $\varepsilon,\mu,n_0(\omega)$ and $\eta_2(\omega)$ for both plates, the Casimir force between these plates is then plotted in Fig. 5(a), and the two-dimensional version is seen in Fig. 5(b). Here, we notice that the Casimir force changes from attractive to repulsive at laser intensity of $I = 1.5\times10^{18}$ W/m^2. This unique feature is not present in the dispersionless case of Figs. 1 and 2. The switching feature remains for smaller interplate spacings, but the feature is lost in the piecewise-dispersive case (Fig. 3), which uses Eq. (4).

To understand the range of frequencies responsible for the change of sign of the Casimir force, the derivative of the force with respect to frequency is plotted (Fig. 6) for (a) $a = 0.2\lambda_0$ and (b) $a = \lambda_0$. For $a = 0.2\lambda_0$, as the intensity increases, the Casimir force derivative around the frequency range ($2\times10^{14} - 2\times10^{15}$ Hz) decreases toward negative values, corresponding to the infrared-optical region of electromagnetic spectrum. The decrease in the Casimir attraction in this region thus leads to an overall Casimir repulsion. However, for $a = \lambda_0$ [Fig. 6(b)], the Casimir attraction decreases on a lower range of frequencies ($10^{14} - 10^{15}$ Hz) as the intensity increases. Hence we deduce that the increase in the plates'

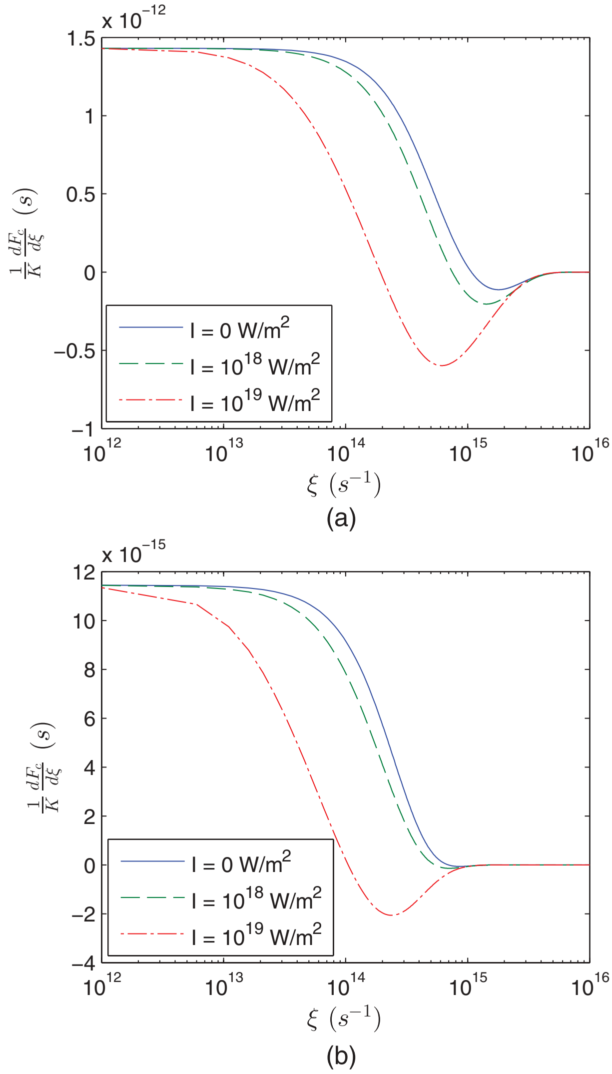

FIG. 6. (Color online) Variation of $dF_c/d\xi$ at different frequencies ξ, for different intensities of impinging laser I. The interplate distance is (a) $a = 0.2\lambda_0$, (b) $a = \lambda_0$. The Casimir force decreases with frequency for sufficiently large laser intensity.

separation will increase the contribution of lower frequencies to the change of the Casimir force.

As a note of feasibility, the intensity of the laser source required ($I \approx 10^{18}$ W/m^2) is achievable with normal diode lasers, which is far less than the current ultrahigh laser intensity $I \approx 10^{26}$ W/m^2 [37], thus enabling practical control over the Casimir force via optical means. For laser intensity $I = 10^{18}$ W/m^2 (around the Casimir switching intensity), the radiation pressure is $P = \frac{I}{c} = 3 \times 10^9$ Nm^{-2}, which is significantly larger than the typical Casimir force, in the order $10^3 K \sim 1$ Nm^{-2}, dominates the contribution to the net force if the laser is directed normal to the outer sides of the plates. However, it is the nonlinear optical properties of the *inner* sides of the plates that need to be controlled. Therefore, the laser has to induce the optical Kerr effect on the inner surfaces of the parallel plates. As such, the laser should be directed parallel to the plates and guided along the inner surface of the plates. Thus, the radiation pressure and the heating effect would be negligible.

In addition, there is laser heating if the laser frequency spectrum falls within the resonant frequencies of the materials in the plates. For a broadband laser pulse, there could be some heating since the laser spectrum contains the resonant frequency of the materials in the plates. The heating leads to thermal expansion and the change in the plate spacing. This is when efficient nonlinear optics at the low-intensity level is useful for laser nanophotonics applications. An alternative solution is to use a laser with a spectrum lying outside the resonant region so that the heating may be avoided. Thus there are elaborate physical processes involved when heating and radiation pressure are included, in addition to the Casimir force, but this is beyond the present scope and will be detailed in future work.

V. CONCLUSION

We have analyzed the possibility of controlling the Casimir force using combinations of metamaterials and nonlinear materials exhibiting optical nonlinear Kerr effect. We have shown that the force can be significantly varied and switched between positive and negative values by changing the intensity of the laser. The ability to alter the force due to the quantum vacuum by changing nonlinear optical properties of matter with intense laser sources provides new possibilities of using laser optics to control quantum electrodynamics phenomena. Potential applications include manipulating nanoresonators and integrating optical devices into nanoelectromechanical systems. The physics of the dynamical Casimir force with laser pulse will be explored in future work using another approach since Eq. (1) does not provide transient information for the Casimir force.

ACKNOWLEDGMENTS

This work is supported by the Ministry of Higher Education (MOHE)/University of Malaya HIR Grant No. A-000004-50001 and the MOHE ERGS Grant No. ER014-2011A.

APPENDIX: TERMS IN $G(x)$

The expressions due to contributions of various physical processes to $G(x)$ in Eq. (7) are given below [36]:

$$\text{Two-photon absorption}: \quad \frac{1}{(2x)^6}\left[-\frac{3}{8}x^2(1-x)^{-1/2} + 3x(1-x)^{1/2} - 2(1-x)^{3/2} + 2\Theta(1-2x)(1-2x)^{3/2}\right]$$

$$\text{Raman}: \quad \frac{1}{(2x)^6}\left[-\frac{3}{8}x^2(1+x)^{-1/2} - 3x(1+x)^{1/2} - 2(1+x)^{3/2} + 2(1+2x)^{3/2}\right]$$

$$\text{Linear Stark}: \quad \frac{1}{(2x)^6}[2-(1-x)^{3/2}-(1+x)^{3/2}]$$

$$\text{Quadratic Stark}: \quad \frac{1}{2^{10}x^5}\left[(1-x)^{-1/2}-(1+x)^{-1/2}-\frac{x}{2}(1-x)^{-3/2}-\frac{x}{2}(1+x)^{-3/2}\right]$$

$$\text{Divergent term}: \quad \frac{1}{(2x)^6}\left[-2-\frac{35x^2}{8}+\frac{x}{8}(3x-1)(1-x)^{-1/2}-3x(1-x)^{1/2} + (1-x)^{3/2}+\frac{x}{8}(3x+1)(1+x)^{-1/2}+3x(1+x)^{1/2}+(1+x)^{3/2}\right],$$

where Θ is the Heaviside step function.

[1] H. B. G. Casimir, Proc. K. Ned. Akad. Wet. **51**, 793 (1948).
[2] T. H. Boyer, Phys. Rev. **174**, 1764 (1968).
[3] A. Rodriguez, M. Ibanescu, D. Iannuzzi, F. Capasso, J. D. Joannopoulos, and S. G. Johnson, Phys. Rev. Lett. **99**, 080401 (2007).
[4] S. J. Rahi, M. Kardar, and T. Emig, Phys. Rev. Lett. **105**, 070404 (2010).
[5] A. Lambrecht and V. N. Marachevsky, Phys. Rev. Lett. **101**, 160403 (2008).
[6] K. A. Milton, *The Casimir Effect: Physical Manifestations of Zero-Point Energy* (World Scientific, Singapore, 2001).
[7] A. Canaguier-Durand, Paulo A. Maia Neto, A. Lambrecht, and S. Reynaud, Phys. Rev. Lett. **104**, 040403 (2010).
[8] A. Weber and H. Gies, Phys. Rev. Lett. **105**, 040403 (2010).
[9] Y. Yang, R. Zeng, H. Chen, S. Zhu, and M. S. Zubairy, Phys. Rev. A **81**, 022114 (2010).
[10] F. M. Serry, D. Walliser, and G. J. Maclay, J. Appl. Phys. **84**, 2501 (1998).
[11] H. J. De Los Santos, Proc. IEEE **91**, 1907 (2003).
[12] H. B. Chan, V. A. Aksyuk, R. N. Kleiman, D. J. Bishop, and F. Capasso, Phys. Rev. Lett. **87**, 211801 (2001).
[13] F. Capasso, J. N. Munday, D. Iannuzzi, and H. B. Chan, IEEE. J. Quantum. Electron. **13**, 400 (2007).
[14] M. Levin, A. P. McCauley, A. W. Rodriguez, M. T. Homer Reid, and S. G. Johnson, Phys. Rev. Lett. **105**, 090403 (2010).
[15] O. Kenneth, I. Klich, A. Mann, and M. Revzen, Phys. Rev. Lett. **89**, 033001 (2002).
[16] J. N. Munday, F. Capasso, and V. A. Parsegian, Nature (London) **457**, 170 (2009).
[17] J. B. Pendry, A. J. Holden, W. J. Stewart, and I. Youngs, Phys. Rev. Lett. **76**, 4773 (1996).
[18] J. B. Pendry, A. J. Holden, D. J. Robbins, and W. J. Stewart, IEEE Trans. Microwave Theory Tech. **47**, 2075 (1999).
[19] C. H. Raymond Ooi, K. C. Low, R. Higa, and T. Ogawa, J. Opt. Soc. Am. B **29**, 2691 (2012).
[20] D. R. Smith, W. J. Padilla, D. C. Vier, S. C. Nemat-Nasser, and S. Schultz, Phys. Rev. Lett. **84**, 4184 (2000).
[21] C. G. Parazzoli, R. B. Greegor, K. Li, B. E. C. Koltenbah, and M. Tanielian, Phys. Rev. Lett. **90**, 107401 (2003).
[22] H. J. Lezec, J. A. Dionne, and H. A. Atwater, Science **316**, 430 (2007).
[23] S. Zhang, Y. S. Park, J. Li, X. Lu, W. Zhang, and X. Zhang, Phys. Rev. Lett. **102**, 023901 (2009).
[24] S. Zhang, W. Fan, N. C. Panoiu, K. J. Malloy, R. M. Osgood, and S. R. J. Brueck, Phys. Rev. Lett. **95**, 137404 (2005).
[25] U. Leonhardt and T. G. Philbin, New J. Phys. **9**, 254 (2007).
[26] Y. Yang, R. Zeng, J. Xu, and S. Liu, Phys. Rev. A **77**, 015803 (2008).
[27] F. S. S. Rosa, D. A. R. Dalvit, and P. W. Milonni, Phys. Rev. Lett. **100**, 183602 (2008).
[28] V. Yannopapas and N. V. Vitanov, Phys. Rev. Lett. **103**, 120401 (2009).
[29] R.-P. Chen and C. H. Raymond Ooi, Prog. Electro. Res. **121**, 39 (2011).
[30] G. Metalidis and P. Bruno, Phys. Rev. A **66**, 062102 (2002).
[31] M. S. Tomaš, Phys. Rev. A **66**, 052103 (2002).
[32] C. Genet, A. Lambrecht, and S. Reynaud, Eur. Phys. J. Special Topics **160**, 183 (2008).
[33] S. H. Wemple and M. DiDomenico, Phys. Rev. B **3**, 1338 (1971).
[34] R. Slusher, G. Lenz, J. Hodelin, J. Sanghera, L. Shaw, and I. Aggarwal, J. Opt. Soc. Am. B **21**, 1146 (2004).
[35] G. Lenz, J. Zimmermann, T. Katsufuji, M. Lines, H. Hwang, S. Spälter, R. Slusher, S. Cheong, J. Sanghera, and I. Aggarwal, Opt. Lett. **25**, 254 (2000).
[36] M. Sheik-Bahae, D. Hutchings, D. Hagan, and E. Van Stryland, IEEE. J. Quantum. Electron. **27**, 1296 (1991).
[37] S. W. Bahk, P. Rousseau, T. A. Planchon, V. Chvykov, G. Kalintchenko, A. Maksimchuk, G. A. Mourou, and V. Yanovsky, Opt. Lett. **29**, 2837 (2004).