Holographic superconductor models in the non-minimal derivative coupling theory*

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(Received 22 July 2011; revised manuscript received 28 September 2011)

We study a general class of holographic superconductor models via the Stückelberg mechanism in the non-minimal derivative coupling theory in which the charged scalar field is kinetically coupling to Einstein's tensor. We explore the effects of the coupling parameter on the critical temperature, the order of phase transitions and the critical exponents near the second-order phase transition point. Moreover, we compute the electrical conductivity using the probe approximation and check the ratios $\omega_{\rm g}/T_{\rm c}$ for the different coupling parameters.

Keywords: holographic superconductor, non-minimal derivative coupling, Einstein's tensor

PACS: 04.70.–s, 11.25.Tq, 74.20.–z **DOI:** 10.1088/1674-1056/21/4/040403

1. Introduction

One of the most significant discoveries in string theory is the AdS/CFT correspondence (anti de Sitter/conformal field theory correspondence)[1−3] which relates a weakly coupled gravity theory in $(d+1)$-dimensional AdS spacetime to a strongly coupled conformal field theory living on the d-dimensional boundary. It is widely believed now that the AdS/CFT correspondence could provide a new means of studying the strongly interacting condensed matter systems in which the perturbative methods are no longer valid. Thus, this holographic method is expected to give us some insights into the nature of the pairing mechanism in the high temperature superconductors which fall outside of the scope of current theories of superconductivity. In the pioneering papers,[4−8] it was suggested that the spontaneous $U(1)$ symmetry breaking occurring in bulk black holes can be used to build gravitational duals of the transition from a normal state to a superconducting state in the boundary theory. This dual model consists of a system with a black hole and a charged scalar field, in which the black hole admits scalar hair at temperature T smaller than a critical temperature $T_{\rm c}$. The appearance of a hairy AdS black hole means the formation of scalar condensation in the boundary conformal field theory (CFT), which indicates that the expectation value of charged operators undergoes $U(1)$ symmetry breaking and then the phase transition occurs. It was argued that this phase transition belongs to the second order one. Due to its potential applications to condensed matter physics, holographic superconductors in various theories of gravity have been investigated in recent years.[9−42] Recently, Franco *et al.*[43] investigated the general models of holographic superconductors in which the spontaneous breaking of a global $U(1)$ symmetry occurs via the Stückelberg mechanism. They found that both the order of the phase transition and the critical exponents for the second phase transition can be tuned by the parameters defined in the models. These generalized holographic superconductor models have also been extended recently to the Gauss–Bonnet gravity[44] and Born–Infeld electrodynamics.[45]

It is well known that the properties of holographic superconductors depend on the coupling between the scalar and the electromagnetic fields. Theoretically, the general form of the action with more couplings

*Project supported by the National Natural Science Foundation of China (Grant No. 10875041), the Program for New Century Excellent Talents in University (Grant No. 10-0165), the Program for Changjiang Scholars and Innovative Research Team in University (Grant No. IRT0964), the Construct Program of Key Disciplines in Hunan Province, and the Project of Knowledge Innovation Program of Chinese Academy of Sciences (Grant No. KJCX2.YW.W10).

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can be expressed as

$$S = \int \mathrm{d}^4x\sqrt{-g}[f(\psi, R, R_{\mu\nu}R^{\mu\nu}, R_{\mu\nu\rho\sigma}R^{\mu\nu\rho\sigma}) + K(\psi, \partial_\mu\psi\partial^\mu\psi, \nabla^2\psi, R^{\mu\nu}\partial_\mu\psi\partial_\nu\psi, \cdots) + V(\psi) + Y(\psi)\mathscr{L}_m], \quad (1)$$

where f, K, and Y are arbitrary functions of the corresponding variables, $\mathscr{L}_\mathrm{m}$ is the Lagrangian for other matter fields. Obviously, the nonlinear functions f, K, and Y provide the most non-minimal couplings among fields and the background spacetime. These new couplings modify the usual Klein–Gordon equation and Einstein–Maxwell equation so that the equations of motion for the scalar and electromagnet fields are no longer generally the second-order differential equations, which may change the properties of holographic superconductors in the AdS spacetime. Recently, Aprile *et al.*[46] considered a special case of the action (1) in which the system contains the couplings among a scalar field, electromagnetic field and the cosmological constant, so that the action has a form

$$S = \int \mathrm{d}^4x\sqrt{-g}\Big[R - \frac{1}{4}G(\psi)F^{\mu\nu}F_{\mu\nu} + \frac{6}{L^2}U(\psi) - \frac{1}{2}\partial_\mu\psi\partial^\mu\psi - \frac{1}{2}J(\psi)A_\mu A^\mu\Big]. \quad (2)$$

They studied the properties of holographic superconductors and found that some aspects of the quantum critical behaviour strongly depend on the choice of couplings $G(\psi)$, $U(\psi)$, and $J(\psi)$.

Another interesting model is that the scalar field in the action (1) is kinetically coupling with Einstein's tensor via the coupling term $\frac{b}{2}\partial_\mu\psi\partial^\mu\psi$, where b is the coupling constant with dimensions of lengthsquared. This new coupling can be regarded as the interaction between the kinetic term of a scalar field and the background spacetime. Therefore, this kind of theory is also called the non-minimal derivative coupling theory. Sushkov found[47] that the equation of motion for the scalar field can be reduced to second-order differential equation in this model, which means that the theory is a "good" dynamical theory from the point of view of physics. This non-minimal derivative coupling theory has been investigated further in recent years.[47–53] In cosmology, the main motivations are to probe the effects of this new coupling on the properties of the universe's evolution. The investigations[47–50] show that such a coupling provides not only a possible explanation to the accelerated expansion of our universe, but also a natural mechanism to solve the problem of a graceful exit from inflation in the early universe without any fine-tuned potential. The main motivations in black hole physics are to see whether this coupling modifies the dynamical behaviours of the scalar field and changes the quantum properties of the black hole. It was shown that the coupling between a scalar field and Einstein's tensor changes the stability of the black hole and enhances the Hawking radiation of the black hole.[51–53]

Previous investigations of holographic superconductors have focused mainly on the interaction between the matter fields. To the best of our knowledge, it is still an open question whether the coupling between a scalar field and Einstein's tensor changes the properties of the holographic superconductor in the AdS black hole spacetime. The main purpose of this paper is to investigate the features of holographic superconductors in the models in which a charged scalar field is kinetically coupling to Einstein's tensor and probes the effects of such a coupling on physical quantities and on the dynamics of phase transitions.

This paper is organized as follows. In Section 2, we will study the scalar condensation and the phase transitions for a general class of the holographic superconductor models via the Stückelberg mechanism as the charged scalar field is kinetically coupling to Einstein's tensor. In Section 3, we will probe the effects of the coupling parameter and other model parameters on the conductivity of the charged condensates. Finally, we will conclude our main results in the last section.

2. General holographic superconductor models in the non-minimal derivative coupling theory

We consider the action of the scalar field coupling to the Einstein's tensor $G^{\mu\nu}$ in the AdS background

$$S = \int \mathrm{d}^4x\sqrt{-g}\Big[R - \Lambda - \frac{F^2}{4} - \frac{|D_\mu\tilde{\psi}D^\mu\tilde{\psi}|}{2} - \frac{b|G^{\mu\nu}D_\mu\tilde{\psi}D_\nu\tilde{\psi}|}{2} - \frac{m^2|\tilde{\psi}^2|}{2} - V(|\tilde{\psi}|)\Big], \quad (3)$$

where $D_\mu = \partial_\mu - \mathrm{i}A_\mu$. As in Ref. [43], re-scaling the charged scalar field $\tilde{\psi} = \psi\,\mathrm{e}^{\mathrm{i}p}$ with real ψ and p, we can obtain the generalized Stückelberg Lagrangian action in the non-minimal derivative coupling theory

$$S = \int \mathrm{d}^4x\sqrt{-g}\Big[R - \Lambda - \frac{F^2}{4} - \frac{(g^{\mu\nu} + bG^{\mu\nu})\partial_\mu\psi\partial_\nu\psi}{2} - \frac{m^2\psi^2}{2} - \frac{|J(\psi)|(g^{\mu\nu} + bG^{\mu\nu})(\partial_\mu p - A_\mu)(\partial_\nu p - A_\nu)}{2} - V(\psi)\Big], \quad (4)$$

with the gauge symmetry $A_\mu \to A_\mu + \partial_\mu\alpha$ together with $p \to p + \alpha$. Here $J(\psi)$ is a function of ψ, which is taken as

$$J(\psi) = \psi^2 + c_\gamma\psi^\gamma + c_4\psi^4, \quad (5)$$

with the model parameters c_γ, γ, and c_4.[43–45] In the probe limit, the backreactions on the background metric from the matter field is negligible. Here we adopt such a limit so that we can neglect the influence of the coupling terms containing the factor $bG^{\mu\nu}$ in the action (4) on the metric for simplicity.

One of the most simple AdS black holes is the planar Schwarzschild one, which can be described by a metric

$$\mathrm{d}s^2 = -f(r)\mathrm{d}t^2 + \frac{1}{f(r)}\mathrm{d}r^2 + r^2(\mathrm{d}x^2 + \mathrm{d}y^2), \quad (6)$$

with

$$f(r) = \frac{r^2}{L^2} - \frac{2M}{r}, \quad (7)$$

where L is the radius of AdS and M is the mass of black hole. The Hawking temperature is

$$T_{\mathrm{H}} = \frac{3r_{\mathrm{H}}}{4\pi L^2}, \quad (8)$$

where r_{H} is the event horizon of the black hole. The Einstein's tensor $G^{\mu\nu}$ in the Schwarzschild AdS black hole (6) is of a form

$$G^{\mu\nu} = \frac{3}{L^2}g^{\mu\nu}. \quad (9)$$

Substituting Eqs. (6) and (9) into Eq. (4) and taking the ansatz

$$A_\mu = (\phi(r), 0, 0, 0), \quad \psi = \psi(r), \quad (10)$$

we find that the equations of motion for the complex scalar field ψ and electrical scalar potential $\phi(r)$ can be written as

$$\psi'' + \left(\frac{f'}{f} + \frac{2}{r}\right)\psi' + \frac{\phi^2}{2f^2}\frac{\mathrm{d}J(\psi)}{\mathrm{d}\psi} - \frac{m^2L^4\psi}{(L^2 + 3b)f} = 0, \quad (11)$$

and

$$\phi'' + \frac{2}{r}\phi' - \left(1 + \frac{3b}{L^2}\right)\frac{J(\psi)}{f}\phi = 0, \quad (12)$$

respectively. Here a prime denotes the derivative with respect to r and we use the gauge freedom to fix $p = 0$. At first sight, it seems that the coupling factor b only plays a role of modifying the mass of the scalar field by a factor $(L^2 + 3b)^{-1}$. However, from Eq. (12), we can find that the coupling factor b also changes the current j^μ in the Maxwell equation. Thus, by comparing with the mass m of the scalar field, the factor b will bring us more richer properties for holographic superconductors in the Schwarzschild AdS black hole.

In order to solve the nonlinear equations (11) and (12) numerically, we need to seek the boundary conditions for ϕ and ψ near the black hole horizon $r \sim r_{\mathrm{H}}$ and at the asymptotic AdS boundary $r \to \infty$. The regularity condition at the horizon gives the boundary conditions $\phi(r_{\mathrm{H}}) = 0$ and

$$\psi = \frac{3(L^2 + 3b)r_{\mathrm{H}}}{m^2L^4}\psi'.$$

At the asymptotic AdS boundary $r \to \infty$, the scalar field ψ and the electric potential ϕ can be approximated as

$$\psi = \frac{\psi_-}{r^{\lambda_-}} + \frac{\psi_+}{r^{\lambda_+}}, \quad (13)$$

and

$$\phi = \mu - \frac{\rho}{r}, \quad (14)$$

with

$$\lambda_\pm = \frac{3}{2} \pm \sqrt{\frac{9}{4} + \frac{m^2L^4}{L^2 + 3b}}. \quad (15)$$

In the dual field theory, the constants μ and ρ are interpreted as the chemical potential and charge density, respectively. The coefficients ψ_- and ψ_+ correspond to the vacuum expectation values of the condensate operators $\mathcal{O}_\pm$ respectively. Since both of the falloffs are normalizable for ψ, one can impose the boundary condition that either ψ_- or ψ_+ vanishes, which ensures that the theory is stable in the asymptotic AdS region.[54] The choices of the boundary condition $\psi_- = 0$ or $\psi_+ = 0$ will not affect qualitatively our results. Thus, we here set $\psi_- = 0$, $L = 1$, and $m^2L^2 = -2$ for convenience. In doing so, we

can investigate the properties of the scalar condensate $\langle \mathcal{O}_+ \rangle = \psi_+$ for fixed charge density by solving the equations of motion (11) and (12) numerically.

Let us now to study how the phase transition depends on the coupling parameter b and the model coefficients c_γ, γ, and c_4 in $J(\psi)$. In Fig. 1, we present the influence of the parameters b and c_4 on the phase transition for fixed $c_\gamma = 0$. We find that the coupling parameter b and the model parameters c_4 have obvious different effects on the critical temperature. In the case $c_4 < 1$, we find that only second-order phase transition occurs in the formation of scalar hair and the critical temperature does not depend on the coefficient c_4. These properties of holographic superconductors are similar to those in the case that the scalar field is not coupling with Einstein's tensor. However, with the increase of the coupling parameter b, the critical temperature decreases, which means that due to the coupling between the scalar field and Einstein's tensor, the formation of the scalar condensate is hard to achieve. It can be explained by the fact that the kinetic coupling form increases the kinetic energy of the scalar field, which makes the scalar field more difficult to condense. For the $c_4 \geq 1$, it was argued that for the case $b = 0$ the behaviour of the scalar condensate means that the phase transition changes from the second order to the first order. Here we choose $c_4 = 1.2, 1.4, 1.6$, and 2.0, and probe the effect of b on the transition point due to phase transition from the second order to the first order. Figure 1 shows that the bigger the value of b, the more difficult it is for transition to occur. The critical value of b_c separating the second-order and first-order phase transitions is listed in Table 1 for selected c_4 within the interval [1.2, 2.0]. Comparing with the discussions in Ref. [44], one can find that the influence of b on the phase transition is different from that of the Gauss–Bonnet coupling parameter α.

Table 1. The critical value of b_c which can separate the first- and second-order behaviour for different $J(\psi) = \psi^2 + c_4\psi^4$.

c_4	1.2	1.4	1.6	2.0
b_c	0.1	0.2	0.3	0.5

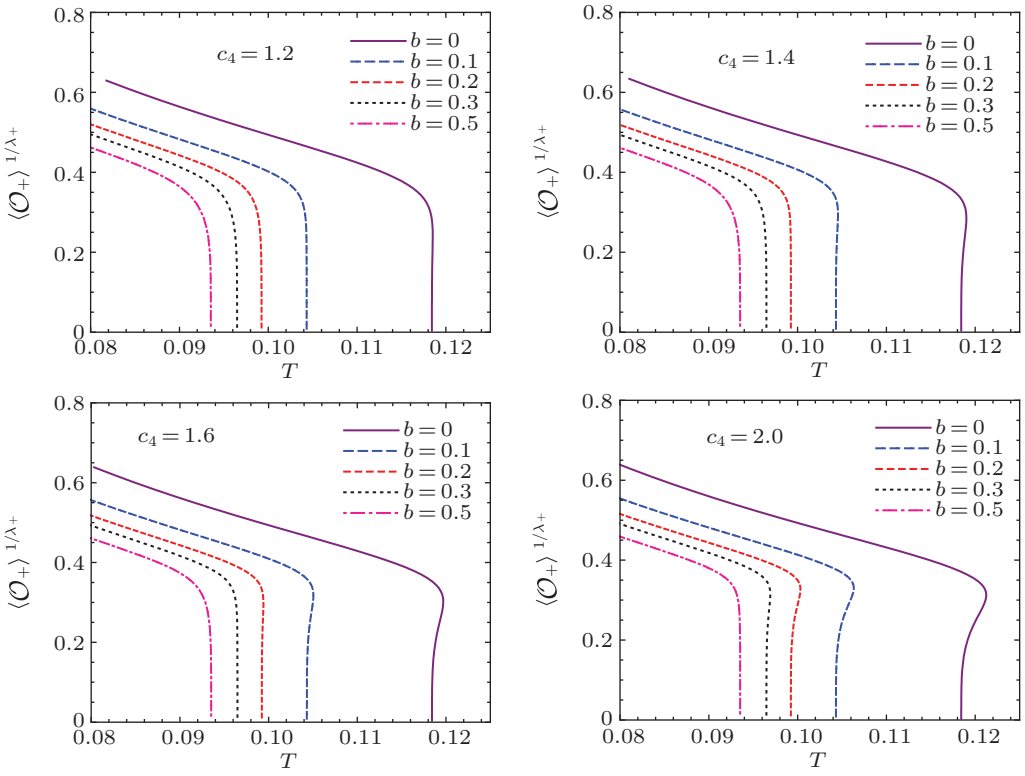


Fig. 1. (colour online) The condensate $\langle \mathcal{O}_+ \rangle^{1/\lambda_+}$ as a function of temperature at fixed value $c_\gamma = 0$ for different b and c_4. It shows that the different values of these parameters not only change the formation of the scalar hair, but also affect the separation between the first- and second-order phase transitions. The five lines in each panel from left to right correspond to decreasing b, i.e, 0.5, 0.3, 0.2, 0.1, and 0.

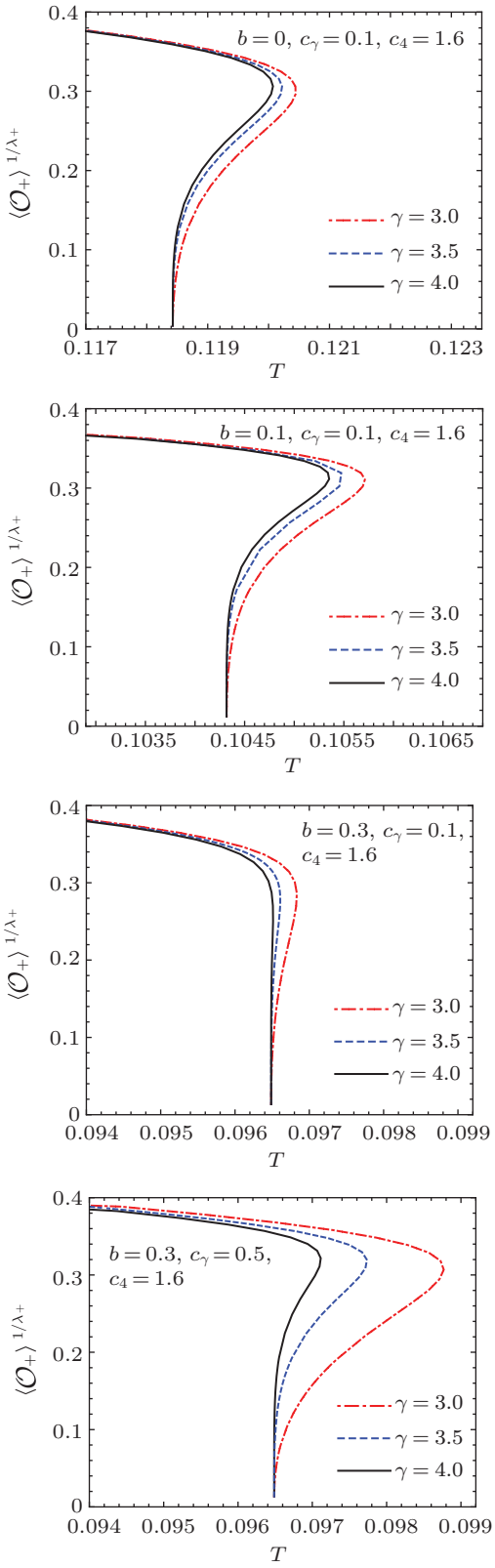


Fig. 2. (colour online) The condensate $\langle\mathcal{O}_+\rangle^{1/\lambda_+}$ as a function of temperature at fixed values c_γ for different values of b and γ. It shows that the type of phase transition depends on the coupling parameter b, model parameters c_γ and γ. The three lines in each panel from left to right correspond to decreasing γ, i.e, 4, 3.5, and 3.

We also consider the case $c_\gamma \neq 0$ for the model $J(\psi) = \psi^2 + c_\gamma\psi^\gamma + c_4\psi^4$. From Fig. 2, we find that the critical temperature increases with the coefficient c_γ and decreases with the power γ for a fixed coupling parameter b, which is consistent with that obtained in the case $b = 0$. For the fixed model parameters c_γ and γ, we find that the presence of b leads to the critical temperatures for two types of phase transitions being much lower, and the transition point from the second order to the first order more difficult. Moreover, we check the critical behaviours of the condensate $\langle\mathcal{O}_+\rangle$ near the second-order phase transition point with different values of b and γ at fixed $c_\gamma = -1$ and $c_4 = 0.5$. From

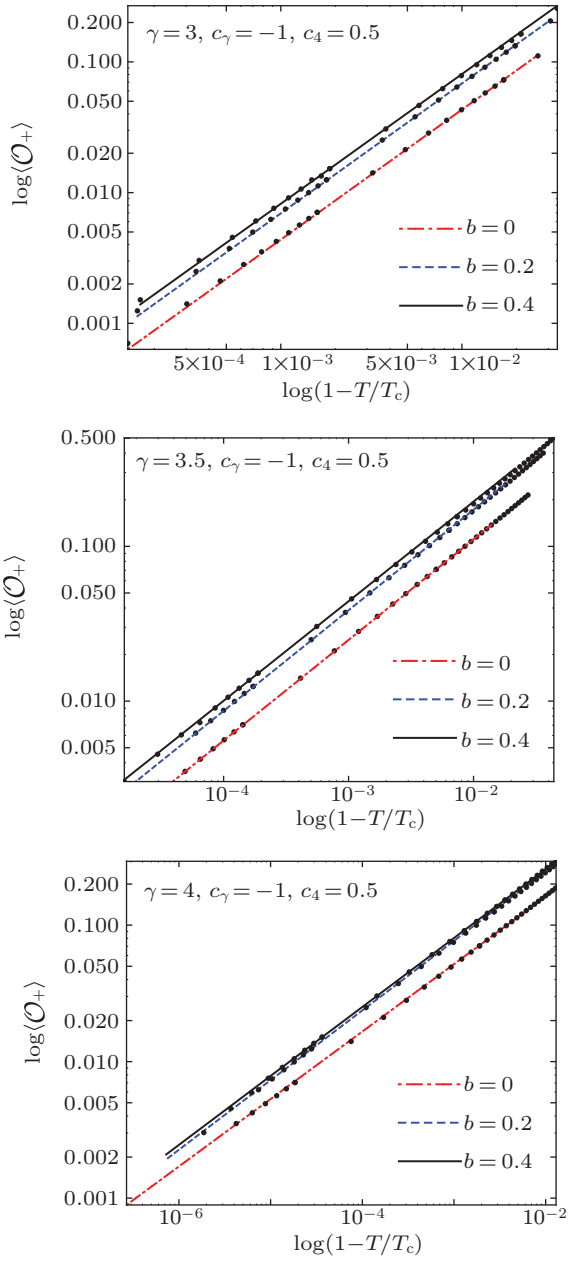


Fig. 3. (colour online) The condensate $\langle\mathcal{O}_+\rangle$ versus $1-T/T_c$ in logarithmic scale with different values of b and γ, which shows that the slope is independent of b but sensitive to γ.

Fig. 3, we find that the critical exponent β can be approximated as

$$\beta \simeq \frac{1}{\gamma - 2}. \tag{16}$$

Obviously, the critical exponent β is determined only by the model parameters in $J(\psi)$ and is independent of the coupling parameter b. Combining with the results obtained in Refs. [43], [44], and [46], we find that the dependence of the critical exponent β near the second-order phase transition point only on the model parameter γ could be a universal property in such a kind of general models for holographic superconductors.

3. The electrical conductivity

In this section we will investigate the electrical conductivity when the scalar field is coupling to Einstein's tensor and see what is the effect of the coupling parameter b and the model parameters (c_γ, γ, and c_4) on electrical conductivity in the planar Schwarzschild AdS black hole spacetime.

Following the standard procedure in Refs. [4]–[8], we suppose that the perturbation of the vector potential is of translational symmetry and time dependence as $\delta A_x = A_x(r)\,\mathrm{e}^{-\mathrm{i}\omega t}$. In the probe approximation, the effect of the perturbation of metric can be ignored. Thus, the equation of motion for δA_x can be written as

$$A_x'' + \frac{f'}{f}A_x' + \left[\frac{\omega^2}{f^2} - (1+3b)\frac{J(\psi)}{f}\right]A_x = 0. \tag{17}$$

As b tends to zero, the above equation can reduce to that in the case that the scalar field is not coupling with Einstein's tensor. Since there exists only the ingoing wave at the black hole horizon, the boundary condition on A_x near $r \sim r_{\mathrm{H}}$ is $A_x = f^{-\mathrm{i}\omega/3r_{\mathrm{H}}}$. In the asymptotic AdS region, one can find easily that A_x behaves as

$$A_x = A_x^{(0)} + \frac{A_x^{(1)}}{r}. \tag{18}$$

According to the AdS/CFT, we can express the conductivity as

$$\sigma(\omega) = \frac{\langle J_x\rangle}{E_x} = -\frac{\mathrm{i}\langle J_x\rangle}{\omega A_x} = -\mathrm{i}\frac{A_x^{(1)}}{\omega A_x^{(0)}}. \tag{19}$$

Solving the equation of motion (17) numerically, we can obtain the conductivity for the general forms of function $J(\psi) = \psi^2 + c_\gamma\psi^\gamma + c_4\psi^4$. Here we set $c_4 = 0$ and $m^2L^2 = -2$ for clarity.

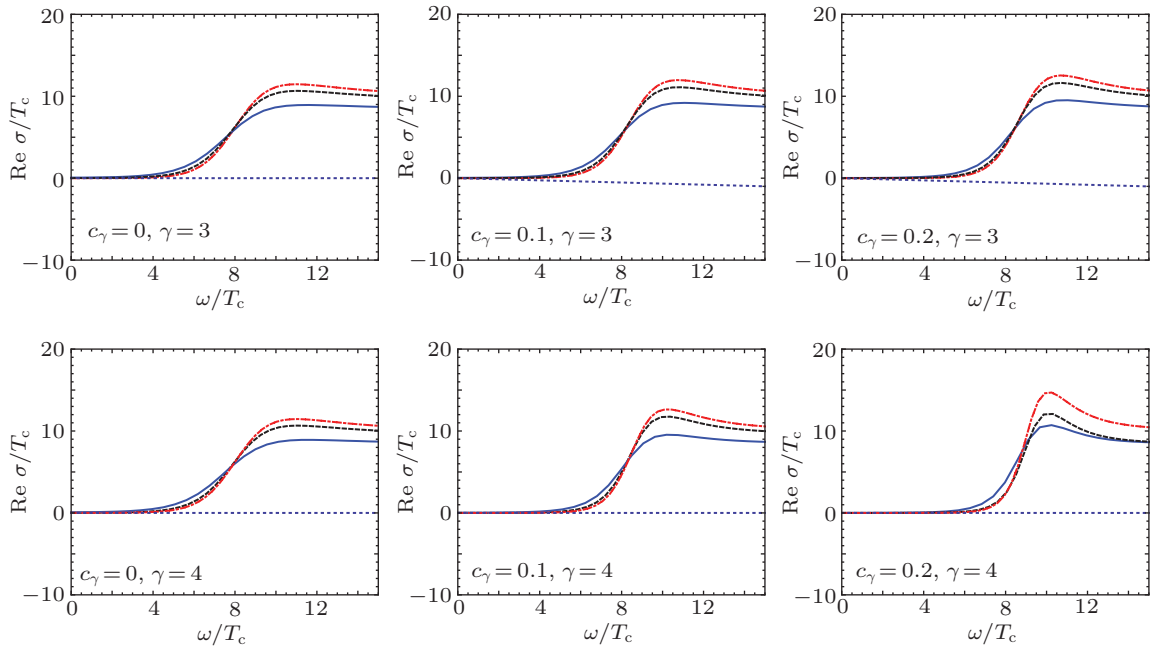


Fig. 4. (colour online) The real part of the conductivity at fixed values of b for different models with $J(\psi) = \psi^2 + c_\gamma\psi^\gamma$. The solid, dashed, and dotted–dashed lines correspond to the cases with $b = 0$, 0.1, and 0.2, respectively.

In Figs. 4 and 5, we plot the frequency-dependent conductivity for operator $\langle \mathcal{O}_+ \rangle$ for different values of b, c_γ, and γ. Fixing the coupling parameter b, the gap frequency ω_g increases with c_γ for fixed γ, and with γ for fixed c_γ. These behaviours of the gap frequency ω_g are also observed in the case $b = 0$. For fixed model parameters c_γ and γ, we find that the gap frequency ω_g becomes bigger for the larger b. It implies that the presence of the coupling parameter b enhances the strength of the strong coupling in holographic superconductors. Our results show that not only the form of the model function $J(\psi)$, but also the coupling between the scalar field and Einstein's tensor of the background affect the so-called universal relation $\omega_g/T_c \simeq 8$. Moreover, one can see that as the coupling constant b increases, spectral weights are transferred from the high frequency to the low frequency part, which is similar to that in Mott physics.

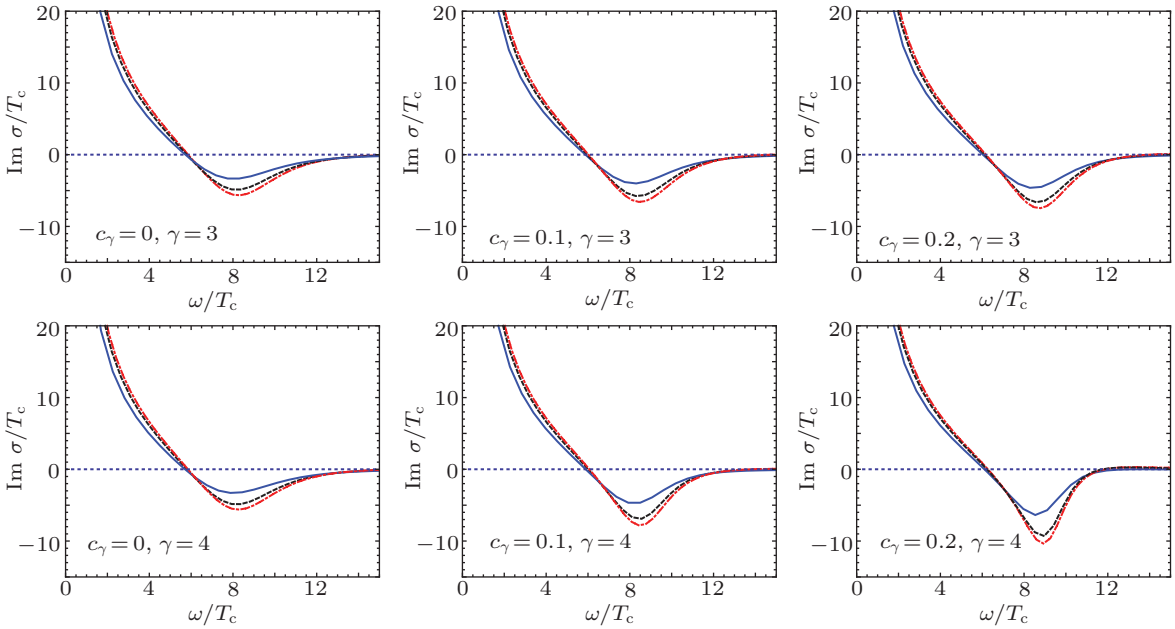


Fig. 5. (colour online) The imaginary part of the conductivity for fixed value of b for different models with $J(\psi) = \psi^2 + c_\gamma \psi^\gamma$. The solid, dashed, and dotted–dashed lines correspond to the cases with $b = 0$, 0.1, and 0.2, respectively.

We now make a comparison between the holographic superconductors in the non-minimal derivative coupling theory and in the Gauss–Bonnet gravity with Born–Infeld electrodynamics.[45] The dependence of the critical temperature T_c and the ratio ω_g/T_c on the non-minimal derivative coupling parameter b is similar to that of T_c and ω_g/T_c on the Born–Infeld coupling parameter in the Gauss–Bonnet gravity. However, we also find that the non-minimal derivative coupling parameter and the Born–Infeld coupling parameter have obviously different effects on the separation point between the first- and second-order phase transitions. The separation point of the phase transition occurs much more difficulty with the increase of the non-minimal derivative coupling parameter b, but more easily with the increase of the Born–Infeld coupling parameter. The mathematical reason is that the Born–Infeld coupling parameter appears only in the equation of motion for the electrical scalar potential $\phi(r)$, while the non-minimal derivative coupling parameter emerges both in the equation of motion for the electrical scalar potential $\phi(r)$ and in that for the scalar field $\psi(r)$.

4. Conclusion

In this paper we have studied a general class of the holographic superconductor models via the Stückelberg mechanism in the non-minimal derivative coupling theory in which the charged scalar field is kinetically coupling with Einstein's tensor. In the probe limit, we found that the coupling parameter b decreases the critical temperature and makes the scalar condensate more difficult to form. Our results also show that both the coupling parameter and the parameters that define $J(\psi)$ can separate the first- and second-order phase transitions. With the increase of b, the transition from the second order to the first

order is also difficult to initialize in this generalized system. This means that the influences of b on the phase transition are different from that of the Gauss–Bonnet coupling parameter α. For the second-order phase transition, we observed that the deviation of the critical exponents from that of the mean-field result is independent of the coupling parameter b and is determined only by the model parameters in the $J(\psi)$.

We also calculated the electric conductivity numerically and found that the gap frequency $\omega_{\rm g}$ depends not only on the form of the model function $J(\psi)$, but also on the coupling between the scalar field and Einstein's tensor of the background. With the increase of the coupling parameter b, the ratio of the gap frequency in conductivity $\omega_{\rm g}$ to the critical temperature $T_{\rm c}$ increases, which implies that the coupling between the scalar field and Einstein's tensor enhances the strength of the strong coupling in holographic superconductors.

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