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Holographic conductivity in the massive gravity with power-law Maxwell field

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ABSTRACT

We obtain a new class of topological black hole solutions in $(n+1)$-dimensional massive gravity in the presence of the power-Maxwell electrodynamics. We calculate the conserved and thermodynamic quantities of the system and show that the first law of thermodynamics is satisfied on the horizon. Then, we investigate the holographic conductivity for the four and five dimensional black brane solutions. For completeness, we study the holographic conductivity for both massless ($m=0$) and massive ($m \neq 0$) gravities with power-Maxwell field. The massless gravity enjoys translational symmetry whereas the massive gravity violates it. For massless gravity, we observe that the real part of conductivity, Re$[\sigma]$, decreases as charge q increases when frequency ω tends to zero, while the imaginary part of conductivity, Im$[\sigma]$, diverges as $\omega \to 0$. For the massive gravity, we find that Im$[\sigma]$ is zero at $\omega = 0$ and becomes larger as q increases (temperature decreases), which is in contrast to the massless gravity. It also has a maximum value for $\omega \neq 0$ which increases with increasing q (with fixed p) or increasing p (with fixed q) for $(2+1)$-dimensional dual system, where p is the power parameter of the power-law Maxwell field. Interestingly, we observe that in contrast to the massless case, Re$[\sigma]$ has a maximum value at $\omega = 0$ (known as the Drude peak) for $p = (n+1)/4$ (conformally invariant electrodynamics) and this maximum increases with increasing q. In this case ($m \neq 0$) and for different values of p, the real and imaginary parts of the conductivity has a relative extremum for $\omega \neq 0$. Finally, we show that for high frequencies, the real part of the holographic conductivity have the power law behavior in terms of frequency, ω^a where $a \propto (n+1-4p)$. Some similar behaviors for high frequencies in possible dual CFT systems have been reported in experimental observations.

1. Introduction

A century after Einstein's discovery namely general relativity, the domain of its applications has become as vast as it covers even condensed matter physics which seemed at the opposite end of physics building compared to gravity [1]. This strange topic which connects gravity to almost all fields of physics (see [2]) is called gauge/gravity duality (GGD); the extended version of AdS/CFT correspondence [3]. GGD has attracted increasing interests during recent years and become one of the most promising fields of physics which is hoped to be able to solve many of unsolved problems in different fields of physics including condensed matter physics.

Real materials in condensed matter physics do not respect the translational symmetry i.e. there is a dissipation in momentum. The momentum dissipation may come from the existence of a lattice or impurities. Although this dissipation has no important influence on the values of some observable, it affects the behavior of some others for instance conductivity. The DC conductivity in the presence of translational symmetry diverges, whereas in the absence of this symmetry (when momentum is dissipating) it has a finite value. In the context of GGD, it is important to study a gravity model which includes holographic momentum dissipation. There are some attempts to construct such gravity model [4]. One of these models proposed by D. Vegh [5], provides an effective bulk description of a theory in which momentum is no longer

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conserved. The conservation of momentum is due to the diffeomorphism invariance of stress–energy tensor in dual theory. In [5], the proposal is to break this symmetry holographically by giving a mass to graviton state. The resulting gravity is therefore *massive gravity*. One of the advantages of this theory is that the black hole solutions of it are solvable analytically and therefore it is an excellent toy model to study holographically the properties of materials without momentum conservation.

Thermal behaviors of black hole solutions in the context of massive gravity was explored extensively in recent years [5–8]. Thermodynamics of linearly charged massive black branes has been investigated in [5]. In [6], a class of higher-dimensional linearly charged solutions with positive, negative and zero constant curvature of horizon in the context of massive gravity accompanied by a negative cosmological constant has been presented and thermodynamics and phase structure of these black solutions have been studied in both canonical and grand canonical ensembles. In [7], van der Waals phase transitions of linearly charged black holes in massive gravity have been investigated and it has been shown that the massive gravity can present substantially different thermodynamic behavior in comparison with Einstein gravity. Also it has been shown that the graviton mass can cause a range of new phase transitions for topological black holes which are forbidden for other cases. The properties of massive solutions have been studied in different scenarios [9]. From holographic point of view, the behaviors of different holographic quantities have been studied [5,10–22]. The behavior of holographic conductivity for systems dual to linearly charged massive black branes has been explored in [5]. In [11], a holographic superconductor has been constructed in the massive gravity background. [13] studies holographic superconductor-normal metal-superconductor Josephon junction in the massive gravity. Also the holographic thermalization process has been investigated in this context [14]. Analytic DC thermo-electric conductivities in the context of massive gravity have been calculated in [12]. In massive Einstein–Maxwell-dilaton gravity, DC and Hall conductivities have been computed in [15]. [16] presents a holographic model for insulator/metal phase transition and colossal magnetoresistance within massive gravity. Inspired by the recent action/complexity duality conjecture, it has been shown in [22] that the holographic complexity grows linearly with time in the context of massive gravity.

As we mentioned above, one of the quantities which is affected by momentum dissipation is conductivity. On the other hand, the choice of electrodynamics model has a direct influence on the behavior of conductivity. So, it is worthy to consider the effects of nonlinearity as well as massive gravity on the conductivity of the black hole solutions. It is well-known that the nonlinear electrodynamics brings reach physics compared to the linear Maxwell electrodynamics. For example, Maxwell theory is conformally invariant only in four dimensions and thus the corresponding energy–momentum tensor is only traceless in four dimensions. A natural question then arises: Is there an extension of Maxwell action in arbitrary dimensions that is traceless and hence possesses the conformal invariance? The answer is positive and the invariant Maxwell action under conformal transformation $g_{\mu\nu} \to \Omega^2 g_{\mu\nu}$, $A_\mu \to A_\mu$ in $(n+1)$-dimensions is given by [23],

$$S_m = \int d^{n+1}x\sqrt{-g}(-\mathcal{F})^p,$$

where $\mathcal{F} = F_{\mu\nu}F^{\mu\nu}$ is the Maxwell invariant, provided $p = (n+1)/4$. The associated energy–momentum tensor of the above Maxwell action is given by

$$T_{\mu\nu} = 2\left(pF_{\mu\eta}F_\nu^{\ \eta}\mathcal{F}^{p-1} - \frac{1}{4}g_{\mu\nu}\mathcal{F}^p\right). \tag{1}$$

One can easily check that the above energy–momentum tensor is traceless for $p = (n+1)/4$. Also, quantum electrodynamics predicts that the electrodynamic field behaves nonlinearly through the presence of virtual charged particles that is reported by Heisenberg and Euler [24]. Hence, nonlinear electrodynamics has been subject of much researches [25–27]. This motivates us to extend the linearly charged black hole solutions of massive gravity [5,6] to nonlinearly charged ones in the presence of power-law Maxwell electrodynamics and investigate the thermodynamics of them as well as the behavior of conductivity corresponding to the dual system. In addition to power-law Maxwell electrodynamics, other types of nonlinear electrodynamics have been introduced in [28–30]. In spite of the special property for $p = (n+1)/4$, different aspects of various solutions have been investigated for different p's [31–33]. In the context of AdS/CFT correspondence, the power-law Maxwell field has been considered as electrodynamics source in [34–39].

The layout of this letter is as follows. In section 2, we present the action of the massive gravity in the presence of power-Maxwell electrodynamics and then by varying the action we obtain the field equations. We also derive a class of topological black hole solutions of the field equations in higher dimensions. In section 3, we study thermodynamics of the solutions and examine the first law of thermodynamics for massive black holes with power-law Maxwell field. In section 4, we investigate the holographic conductivity of black brane solutions in the presence of a power-law Maxwell gauge field. In particular, we shall disclose the effects of the power-law Maxwell electrodynamics as well as massive gravity on the holographic conductivity of dual systems. We finish with closing remarks in section 5.

2. Action and massive gravity solutions

The $(n+1)$-dimensional $(n \geq 3)$ action describing Einstein-massive gravity accompanied by a negative cosmological constant Λ in the presence of power-law Maxwell electrodynamics is

$$\mathcal{S} = \int d^{n+1}x\mathcal{L}, \tag{2}$$

$$\mathcal{L} = \frac{\sqrt{-g}}{16\pi}\left[\mathcal{R} - 2\Lambda + (-\mathcal{F})^p + m^2\sum_i^4 c_i\mathcal{U}_i(g,\Gamma)\right], \tag{3}$$

where g and $\mathcal{R}$ are respectively the determinant of the metric and the Ricci scalar and $\Lambda = -n(n-1)/2l^2$ is the negative cosmological constant where l is the AdS radius. $\mathcal{F} = F_{\mu\nu}F^{\mu\nu}$ and $F_{\mu\nu} = \partial_{[\mu}A_{\nu]}$ is electrodynamic tensor where A_ν is vector potential. p determines the nonlinearity of the electrodynamic field. For $p = 1$, the linear Maxwell gauge field will be recovered. In action (2), Γ is the reference metric, c_i's are constants and $\mathcal{U}_i$'s are symmetric polynomials of eigenvalues of the $(n+1)\times(n+1)$ matrix $\mathcal{K}^\mu_\nu \equiv \sqrt{g^{\mu\alpha}\Gamma_{\alpha\nu}}$ so that

$$\mathcal{U}_1 = [\mathcal{K}], \tag{4}$$

$$\mathcal{U}_2 = [\mathcal{K}]^2 - \left[\mathcal{K}^2\right], \tag{5}$$

$$\mathcal{U}_3 = [\mathcal{K}]^3 - 3[\mathcal{K}]\left[\mathcal{K}^2\right] + 2\left[\mathcal{K}^3\right], \tag{6}$$

$$\mathcal{U}_4 = [\mathcal{K}]^4 - 6\left[\mathcal{K}^2\right][\mathcal{K}]^2 + 8\left[\mathcal{K}^3\right][\mathcal{K}] + 3\left[\mathcal{K}^2\right]^2 - 6\left[\mathcal{K}^4\right], \tag{7}$$

where the square root in $\mathcal{K}$ is related to mean matrix square root i.e. $\left(\sqrt{\mathcal{K}}\right)^\mu_{\ \nu}\left(\sqrt{\mathcal{K}}\right)^\nu_{\ \lambda} = \mathcal{K}^\mu_\lambda$ and rectangular brackets mean trace $[\mathcal{K}] \equiv \mathcal{K}^\mu_\mu$. Here m is the massive gravity parameter so that in limit $m \to 0$, one recovers the diffeomorphism invariant Einstein–Hilbert

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