Microwave Conductivity Resonance of Two-Dimensional Hole System

C.-C. Li,[1] L. W. Engel,[2] D. Shahar,[1] D. C. Tsui,[1] and M. Shayegan[1]
[1]*Department of Electrical Engineering, Princeton University, Princeton, New Jersey 08544*
[2]*National High Magnetic Field Laboratory, Florida State University, Tallahassee, Florida 32306*
(Received 8 August 1996; revised manuscript received 24 March 1997)

We have measured microwave conductivity, $\mathrm{Re}(\sigma_{xx})$, of a high quality two-dimensional hole system (2DHS) in the high magnetic field (*B*) insulating phase for frequency (*f*) between 0.2 and 9 GHz. For $\nu < 0.3$, $\mathrm{Re}(\sigma_{xx})$ vs *f* shows a well-defined peak at frequency f_{pk}. As *B* is increased, the maximal $\mathrm{Re}(\sigma_{xx})$ increases. The resonance *Q* (f_{pk} divided by full line width at half maximum) increases linearly with *B*. f_{pk} vs *B* increases, but is nearly flat, at 1.25 GHz, for $B \geq 10$ T. Oscillator strength, *S*, measured by integrating the spectrum, is likewise flat for $B \geq 10$ T. The simultaneously *B*-independent *S* and f_{pk} are inconsistent with the conventional (Fukuyama-Lee) interpretation of the resonance as a Wigner crystal pinning mode. [S0031-9007(97)03876-3]

PACS numbers: 73.40.Hm, 73.50.Mx, 75.40.Gb

In high magnetic field (*B*), two dimensional hole systems (2DHS), like two-dimensional electron systems (2DES), exhibit the fractional quantum Hall effect [1,2] (FQHE), a phenomenon long understood [3] as due to carrier-carrier interactions. Also seen in both 2DES and 2DHS in the high *B* limit are insulating phases, in which carrier-carrier and impurity interactions both play parts. The relative importance of these interactions remains an open question, and one whose answer must depend on the disorder of the sample, its 2D carrier density *n*, and the *B* at which the insulator is observed. A motivation for examining 2DHS as well as 2DES is the larger effective mass m^* for holes. For the 2DHS we study, m^* is around 0.37 electron masses [4], as compared to 0.067 electron masses for a 2DES. The state of a clean 2D system in the high *B* limit is a Wigner crystal (WC) [5], though impurities present in any real system pin the crystal, making it an insulator and breaking it up into domains of linear size *L*. Wigner crystallization is favored at larger $r_s = (n\pi)^{-1/2} m^* e^2 / 4\pi\hbar^2 \epsilon\epsilon_0$ [6] (where ϵ is the dielectric constant of GaAs), and this is consistent with the observation [7] that in high quality dilute 2DHS's, high *B* insulators set in at higher Landau fillings (ν) than in 2DES's.

Many experiments [8–16] have been directed at understanding high *B* insulating phases, primarily in 2DES's. These include observations of threshold conduction [8–10], noise generation [8,9], giant dielectric constant [11], ac-dc interference [12], cyclotron resonance [13], and photoluminescence measurements [14]. In rf or microwave transport experiments [10,15,16], like the one described here, except done on 2DES's, insulators at high *B* exhibit an absorption line that is generally ascribed to a mode in which crystalline domains oscillate within the pinning potential.

Reference [16] presents plots of resonance peaks as $\mathrm{Re}(\sigma_{xx})$ vs frequency, *f*. The resonance peak frequency, f_{pk}, reported in that reference, increases with *B* in an insulator that appears as *B* just above that of the 1/3 fractional quantum Hall liquid (FQHL). Modeling the mode as an oscillator in the magnetic field, the reference argues from the *B* dependence of f_{pk} that the relevant restoring force is *B* dependent, as it would be for a WC whose stiffness increases with *B*, but contrary to models where a fixed mass oscillates in a *B* independent potential. References [15,16] assess finite frequency conductivity quantitatively, and find that according to the oscillator model at least a substantial fraction of the electrons in the sample participate in the resonance.

This paper reports on a microwave resonance in conductivity, $\mathrm{Re}(\sigma_{xx})$, vs frequency, *f*, observed in the high *B* insulator of a high quality 2DHS. The insulator in this sample is reentrant [7,17] about a well-developed 1/3 FQHE. Any resonance in $\mathrm{Re}(\sigma_{xx})$ vs *f* in the insulator at *B* below the 1/3 FQHE is too weak to observe over our instrumental noise, but a strong resonance appears in the insulator at higher *B*. The peak in $\mathrm{Re}(\sigma_{xx})$ vs *f* in this higher *B* insulator is discernible for $\nu \simeq 0.30$. The frequency of the peak, f_{pk}, vs *B* increases, but becomes nearly flat for $B \gtrsim 10$ T ($\nu \leq 0.22$), with $f_{\mathrm{pk}} \approx 1.25$ GHz. *S*, the integrated $\mathrm{Re}(\sigma_{xx})$ vs *f* is likewise nearly *B* independent in that region. σ_{pk}, the maximum $\mathrm{Re}(\sigma_{xx})$ of the peak, increases steadily with *B*. The resonance *Q*, defined as f_{pk} divided by the full width at half maximum, increases linearly with *B* throughout the range where the resonance is observed, and is about 5 at our maximum *B* of 14.4 T. The plots of *S* and f_{pk} vs *B*, taken together, conflict with the standard classical oscillator model [18,19] of the resonance as a mode of a disorder-pinned WC. The sharpness of the peak indicates a small statistical variance in oscillator frequencies, and is therefore a suprising feature for a mode which has its origin in pinning by random impurities.

The experimental measurement of microwave frequency conductivity has been described in an earlier publication [20]. On the top surface of the sample 3500 Å of Al was evaporated and lifted off to form a transmission line, which consists of a 45 μm wide

0031-9007/97/79(7)/1353(4)$10.00

center strip separated from side planes by gaps of width $W = 30\ \mu$m, as shown in the inset of Fig. 1. This transmission line, which is of a type called coplanar waveguide [21], couples capacitively to the 2DHS ~ 3700 Å beneath the sample surface. During the measurements, the center strip is driven relative to the side "ground" planes. The line is designed so that Z_0, the characteristic impedance with the 2DHS absent, is 50 Ω. Dissipation in the 2DHS occurs mainly under the gaps, so in the absence of higher spatial harmonics the experiment is sensitive to σ_{xx} with wave vector $q \lesssim 2\pi/W$. In this work, as in Ref. [16], no evidence of a spatial harmonic series is seen, and in the calculation of $\mathrm{Re}(\sigma_{xx})$ the 2DHS is considered in the low q limit.

The transmitted microwave power was measured and normalized to unity for the case of vanishing σ_{xx}. We calculated the real part of diagonal conductivity of the 2DHS as $\mathrm{Re}(\sigma_{xx}) = W|\ln P|/2Z_0 d$, where P is the normalized transmitted power and $d = 28$ mm is the total length of the transmission line. This formula is valid in the case of low loss, high f, and negligible reflections. Analysis of the system of line and 2DHS in the quasi-TEM approximation, without these assumptions, indicates that this formula is correct to about 15% under the experimental conditions. An additional error in $\mathrm{Re}(\sigma_{xx})$ of about $\pm 0.2\ \mu$S exists due to the process of normalizing P. The apparatus is typically 20 times more sensitive to $\mathrm{Re}(\sigma_{xx})$ than it is to $\mathrm{Im}(\sigma_{xx})$.

Both the sample and the detectors were loaded in the mixing chamber of a dilution refrigerator. We varied the input power to ensure that the applied microwaves were not causing heating at our operating $T \sim 50$ mK.

The sample was a $GaAs/Al_{0.35}Ga_{0.65}As$ heterojunction grown on (311)A GaAs substrate, so that a 2DHS was realized with Si doping [22]. Carrier density was $5.37 \times 10^{10}\ \mathrm{cm}^{-2}$, and mobility was about $2.5 \times 10^5\ \mathrm{cm}^2/\mathrm{V\,sec}$ at 350 mK. dc transport for the sample was measured by means of In/Zn Ohmic contacts on the edges of the sample, outside of the transmission line pattern. The diagonal resistance (R_{xx}) vs B is shown in Fig. 1(a) for $T = 30$, 85, and 130 mK. R_{xx} increases with decreasing T, typical of an insulator, for $3.55 \le B \le 6.25$ T and $B \ge 6.97$ T ($0.62 \ge \nu \ge 0.36$ and $\nu \le 0.32$), so insulator exists both at higher and lower B than the 1/3 FQHE, which is well developed. The 2/5 and 3/5 FQHE's appear as dips in R_{xx}. The sample in this work was taken from the same wafer (M259) used by Santos *et al.* [7] in a previous observation of reentrance of insulating behavior around the 1/3 FQHE in a 2DHS.

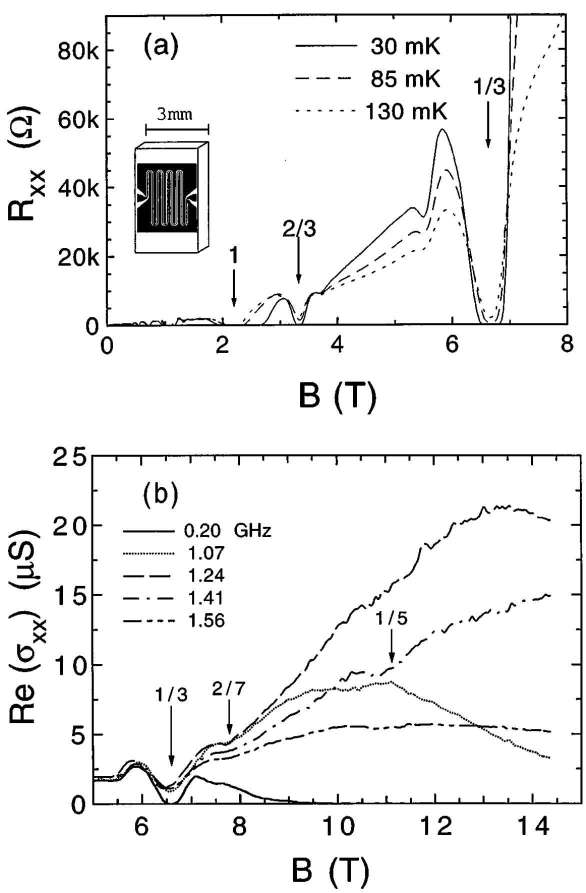

FIG. 1. (a) dc magnetoresistance vs magnetic field, at $T =$ 30, 85, and 130 mK. The inset shows the pattern of transmission line on sample surface, with black indicating the evaporated Al film. (b) Real part of diagonal conductivity vs magnetic field for several frequencies, $T = 50$ mK.

$\mathrm{Re}(\sigma_{xx})$ vs B traces appear in Fig. 1(b) for several f's. The microwave measurements are carried to much higher B than the dc measurements, at the working T of 50 mK, since the dc R_{xx} becomes so large as to be difficult to measure. In the insulator at $\nu > 0.36$, $\mathrm{Re}(\sigma_{xx})$ remains small so that any nonmonotonic f dependence is hidden by the noise, though we do not rule out the possibility that a resonance may exist for $\nu > 0.36$. The 1/3 FQHE minimum in $\mathrm{Re}(\sigma_{xx})$ vs B weakens uniformly with increasing f. For $\nu \le 0.32$ ($B \ge 7.0$ T), where the T dependent dc transport indicates there is an insulator for B above the 1/3 FQHE, $\mathrm{Re}(\sigma_{xx})$ exhibits a strong nonmonotonic f dependence. For 0.20 GHz $\mathrm{Re}(\sigma_{xx})$ reaches a maximum of $\sim 2\ \mu$S at ~ 7.1 T, and then vanishes with increasing B for $B \gtrsim 10$ T, while even deep in the insulator the higher f traces can reach $\mathrm{Re}(\sigma_{xx})$ values much greater than any observed for $\nu \ge 1/3$. All the curves show dips around $\nu = 2/7$, and the 1.41 GHz trace shows a notable dip around $B = 11$ T ($\nu = 1/5$).

Figure 2 shows $\mathrm{Re}(\sigma_{xx})$ vs f for several fixed B's in the higher B insulating phase. A single peak in $\mathrm{Re}(\sigma_{xx})$ vs f is discernible for $B \ge 7.4$ T ($\nu \le 0.3$). At 7.42 T, the resonance is rounded and broad, but as B is increased, the resonance becomes sharper and narrower. f_{pk} also increases with B, but for the curves with the resonance well developed, the upward shift in f_{pk} with B is slight.

The development of the resonance with B is summarized in Fig. 3. S is the numerical integral of $\mathrm{Re}(\sigma_{xx})$ vs f over the experimentally observed f range of 0.2 to 9 GHz. f_{pk} and S vs B are plotted together in Fig. 3(a), using left and right vertical axes, which each covers a

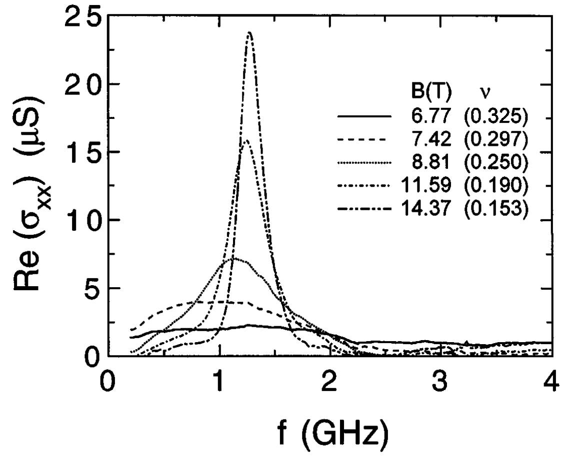

FIG. 2. Real part of diagonal conductivity vs frequency for several magnetic fields, $T = 50$ mK.

factor of 2 range. For B up to about 10 T ($\nu = 0.22$), f_{pk} increases from 1.02 to 1.22 GHz as B is increased. For $B > 10$ T, f_{pk} is nearly independent of B, increasing to only 1.27 GHz by the maximum available B of 14.4 T ($\nu = 0.154$). Significantly, with B between 10 and 14.4 T the S vs B curve follows the f_{pk} vs B curve well, and is likewise nearly independent of B. For the B range above

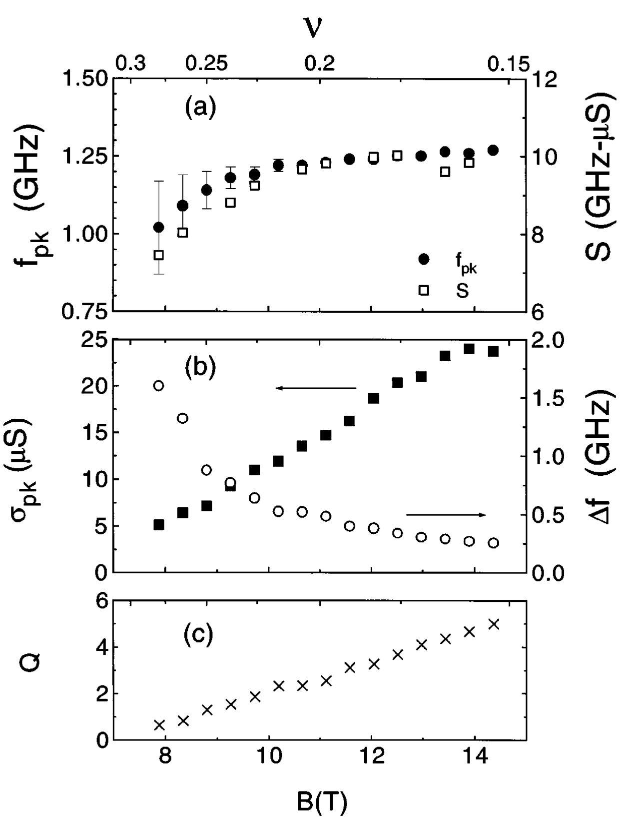

FIG. 3. (a) Peak frequency and integrated absorption of resonances vs magnetic field, $T = 50$ mK. (b) Left axis shows resonance peak heights. Right axis shows full width at half maximum of the resonance. (c) Q of the resonance vs magnetic field.

10 T the resonance is well developed, with no high f tail outside the measured f range, so that S as plotted is a good measure of the oscillator strength.

Figure 3(b) shows σ_{pk} and Δf, the full width at half maximum of the resonance. The peak grows larger and narrower with increasing B throughout the B range over which we observe it. Figure 3(c) shows the quality factor Q defined as $f_{\mathrm{pk}}/\Delta f$, which is seen to increase linearly with B, even beyond 10 T, where f_{pk} is approximately independent of B.

Resonances in high B insulators have been interpreted [10,15,16] as WC pinning modes, using the classical oscillator model of Fukuyama and Lee [18,19]. The present data, particularly the plots of f_{pk} and S vs B, throw doubt on this interpretation. In the Fukuyama-Lee (FL) model, the 2D system, of carrier density n_s, is taken to contain classical oscillators of mass M, which move in harmonic potentials $V_0u^2/2$, where u is a displacement from an equilibrium position, and $V_0 = M\omega_0^2$, with ω_0 an empirical parameter called the pinning frequency. In the case that the system is a pinned WC, M is the mass of a domain of linear size L, so $M = L^2 n_s m^*$, and the pinning potential can include elastic energy of the WC as well as interaction between the domain and the pinning impurities [19]. The FL model predicts two mode frequencies, one above the cyclotron frequency, $\omega_c = eB/m^*$, and one much lower. This lower frequency, ω_-, is in the range of interest, and is compared to data when $\omega_0 \ll \omega_c$, $\omega_- \approx \omega_0^2/\omega_c = V_0/(eBL^2 n_s)$. The FL model predicts the oscillator strength associated with the ω_- mode, which in units of an integral of $\mathrm{Re}(\sigma_{xx})$ with respect to f is $n_s e^2 \omega_0^2/2m^*\omega_c^2 = (n_s e/B)\pi f_{\mathrm{pk}}$. This would imply that when f_{pk} vs B is flat as observed, S vs B should fall off as $1/B$, which is clearly not the case for the data of Fig. 3(a).

An interesting feature of the FL model that could be preserved in a description of the present data is a cancellation of m^* in the expression for f_{pk}, for systems with the same potential, domain size, and density (V_0, L^2, n_s). Our f_{pk} at high B of 1.25 GHz is roughly in agreement with those in 2DES exhibiting single resonances [10,15,16], which at low ν are between 1 and 2 GHz, for electron densities ranging from 4 to 11×10^{10} cm^{-2}.

The width of the resonance gives an upper estimate for the damping of a typical oscillator, since the observed width results from a combination of oscillator damping and inhomogeneous broadening [19]. It is natural to interpret the linear increase of Q with B as due to a decrease in damping, rather than as a reduction in the statistical variance of oscillator frequencies. Because the linear Q vs B does not saturate, even at our highest experimental B of 14.4 T, where a Q of 5 is observed, we can take the observed 14.4 T linewidth to be predominantly due to damping rather than to inhomogenous broadening. At present we have no explanation of the striking linear increase of Q with B. Theories [23] of damping for pinning modes of charge density waves in transition metal trichalcogenides are based on the conductivity of uncondensed carriers. Such a damping mechanism is unlikely to produce a linear Q vs B for the present system, since low T dc conductivity decreases more rapidly than linearly in the insulating phase.

As in previous work on 2DES [15,16], the order of magnitude of the observed f-integrated absorption would be consistent in the context of the FL model with a substantial fraction of the carriers participating. With all holes participating, the predicted $S = (n_s e/B)\pi f_{\mathrm{pk}}$ is 24 μS GHz, for f_{pk} of 1.25 GHz, $B = 14.4$ T. The observed S is about 10 μS GHz at $B = 14.4$ T. Such a large signal is difficult to reconcile with the observed high Q if the standard FL model is retained. The high Q indicates that oscillators in the sample are both weakly damped and similar to one another, a situation that would be easiest to explain, at least in terms of independent oscillators, if the oscillations are dilute.

The f_{pk} vs B curve of Fig. 3(a) exhibits two regions in the insulating phase for $\nu \leq 0.3$: the first region has $7.4 \leq B \leq 10$ T, with f_{pk} increasing with B, and the second has $B \geq 10$ T with f_{pk} constant. The first region is adjacent to the transition from the $1/3$ FQHL, and the increase of f_{pk} with B is probably associated with the transition, possibly reflecting some FQHL correlations remaining in the insulating regime [16,24]. The data suggest a flat f_{pk} vs B may be characteristic of the insulator in the high B limit. This would again point to difficulty with the FL model, since it would require ω_0 to be B dependent, $\omega_0 \propto \omega_c^{1/2}$. This could only be the case if the stiffness of the WC changes with B [16].

To our knowledge there is as yet no model that would resolve the difficulties the data point to in the conventional classical oscillator models. One starting point for explaining the data in this paper may be the high Q, since it implies a narrow distribution that seems inconsistent with a mode of random domains. The problems we describe with the FL pinning mode picture even cast doubt on interpretations where observation of the resonance is taken as proof of a WC phase.

In summary, we have observed a resonance in curves of $\mathrm{Re}(\sigma_{xx})$ vs f for a high-quality 2DHS. Besides being the first measurements of resonant microwave absorption in 2DHS high B insulating phase, the data demand a rethinking of the conventional, classical pinning mode interpretation of the resonances in high B insulators.

We thank A. Millis, N. P. Ong, and P. Platzman for their comments. We acknowledge support from NSF, and L. W. E. acknowledges support from the state of Florida.

[1] D. C. Tsui, H. L. Stormer, and A. C. Gossard, Phys. Rev. Lett. **48**, 1559 (1982).
[2] E. E. Mendez *et al.*, Phys. Rev. B **30**, 1087 (1984).
[3] R. B. Laughlin, Phys. Rev. Lett. **50**, 1395 (1983).
[4] K. Hirakawa *et al.*, Phys. Rev. B **47**, 4076 (1993).
[5] Y. E. Lozovik and V. I. Yudson, JETP Lett. **22**, 11 (1975); P. K. Lam and S. M. Girvin, Phys. Rev. B **30**, 473 (1984); D. Levesque, J. J. Weis, and A. A. McDonald, Phys. Rev. B **30**, 1056 (1984).
[6] X. Zhu and S. G. Louie, Phys. Rev. Lett. **70**, 335 (1993); R. Price, P. M. Platzman, and S. He, Phys. Rev. Lett. **70**, 339 (1993).
[7] M. B. Santos *et al.*, Phys. Rev. Lett. **68**, 1188 (1992); M. B. Santos *et al.*, Phys. Rev. B **46**, 13 639 (1992); H. C. Manoharan and M. Shayegan, Phys. Rev. B **50**, 17 662 (1994).
[8] V. J. Goldman *et al.*, Phys. Rev. Lett. **65**, 2189 (1990).
[9] Y. P. Li *et al.*, Phys. Rev. Lett. **67**, 1630 (1991).
[10] F. I. B. Williams *et al.*, in *Localization and Confinement of Electrons in Semiconductors,* edited by F. Kuchar, H. Heinrich, and G. Bauer (Springer-Verlag, Berlin, 1990); E. Y. Andrei *et al.*, Phys. Rev. Lett. **60**, 2765 (1988); and comment by H. L. Stormer and R. L. Willett, *ibid.* **62**, 972 (1989); reply by E. Y. Andrei *et al.*, *ibid.* **62**, 973 (1989).
[11] Y. P. Li *et al.*, Solid State Commun. **95**, 619 (1995).
[12] Y. P. Li *et al.*, Solid State Commun. **96**, 379 (1995); **99**, 255 (1996).
[13] For example, T. A. Kennedy *et al.*, Solid State Commun. **21**, 459 (1977); B. A. Wilson, S. J. Allen, and D. C. Tsui, Phys. Rev. B **24**, 5887 (1981); M. Besson *et al.*, Semicond. Sci. Technol. **7**, 1274 (1992); G. M. Summers *et al.*, Phys. Rev. Lett. **70**, 2150 (1993).
[14] H. Buhmann *et al.*, Phys. Rev. Lett. **66**, 926 (1991); E. M. Goldys *et al.*, Phys. Rev. B **46**, 7957 (1992); I. V. Kukushkin *et al.*, Phys. Rev. B **45**, 4532 (1992).
[15] M. A. Paalanen *et al.*, Phys. Rev. B **45**, 11 342 (1992); **45**, 13 784 (1992).
[16] L. W. Engel *et al.*, Solid State Commun. (to be published).
[17] H. W. Jiang *et al.*, Phys. Rev. Lett. **65**, 633 (1990).
[18] H. Fukuyama and P. A. Lee, Phys. Rev. B **17**, 535 (1978); **18**, 6245 (1978).
[19] B. G. A. Normand, P. B. Littlewood, and A. J. Millis, Phys. Rev. B **46**, 3920 (1992); A. J. Millis and P. B. Littlewood, Phys. Rev. B **50**, 17 632 (1994).
[20] L. W. Engel *et al.*, Phys. Rev. Lett. **71**, 2638 (1993).
[21] C. P. Wen, IEEE Trans. Microwave Theory Tech., **MTT-17**, 1087 (1969).
[22] W. I. Wang, E. E. Mendez, and Y. Iye, J. Appl. Phys. **60**, 1834 (1986).
[23] See, for example, P. B. Littlewood, Phys. Rev. B **36**, 3108 (1987).
[24] S. Kivelson, D.-H. Lee, and S.-C. Zhang, Phys. Rev. B **46**, 2223 (1992).