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Tuneable Complex Permittivity and Permeability of Silver-Epoxy Nano-Composite by Percolation Effect Over a Wide Bandwidth

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Abstract -The percolation theory has garnered extensive attention over the last four decades in the context of permittivity and conductivity, with a noticeable gap in the exploration of permeability. This research delves into the percolation phenomena's impact on the permittivity, permeability, and conductivity of a silver-epoxy nano-composite. The identified percolation threshold falls within the range of 26.3% to 26.4%. At this threshold, the dielectric constant exhibits a remarkable increase, reaching up to 390, accompanied by a permeability of 0.31 in close proximity to the threshold. The critical exponents for permittivity, conductivity, and susceptibility, determined through fitting, are ***s=1.3469***, ***q=3.1190***, and ***u=0.6756*** respectively.

Method

The preparation of sample stars from the cleaning of the copper waveguide. The waveguide goes through copper polishing solution, water, acetone and isopropanol. Then it was sandwiched by Teflon holders. Next, the composite is prepared by adding the resin (Epoxy A) and mixed with the nanopowder, then the hardener (Epoxy B). When the mixture shows little liquidity, it was poured in to the holder. Then the holder as a whole was brought into a hand-made oven, and be left for 3 hours at about 80 degree for the composite to cure. After the composite was cured, it was polished, so that the surface is nice and smooth. The procedure is given in Fig. 1(a), and (c), whereas the SEM image of nanopowder is given in (b).

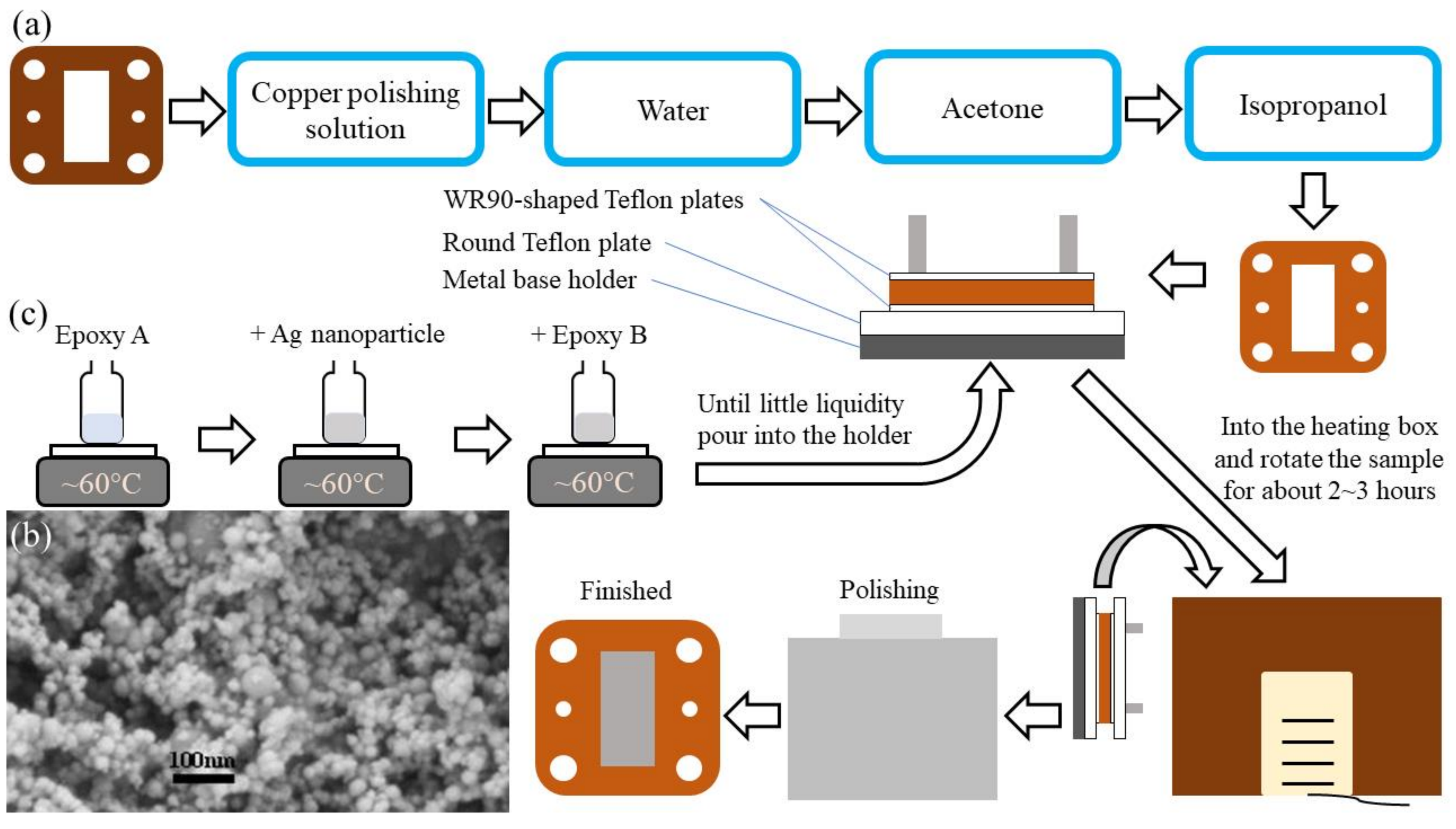

Fig. 1

The measurements were conducted using the Keysight PNA-X N5247B, and S-parameter from 8.2GHz to 12.4GHz measured. The acquired data was analysed through the Fresnel equation and the infinite geometric sequence, by MATLAB (R2021b), allowing the retrieval of permittivity and permeability from the S-parameters.

As for the conductivity, a plate featuring a 3D-printed array of holes in 10 by 6 with a separation of 1mm was utilised. Using Arduino UNO, I employed two probes to measure the resistance between consecutive holes. The measurement was conducted under a constant 5V DC voltage. All measurement was operated at room temperature (300K).

Result

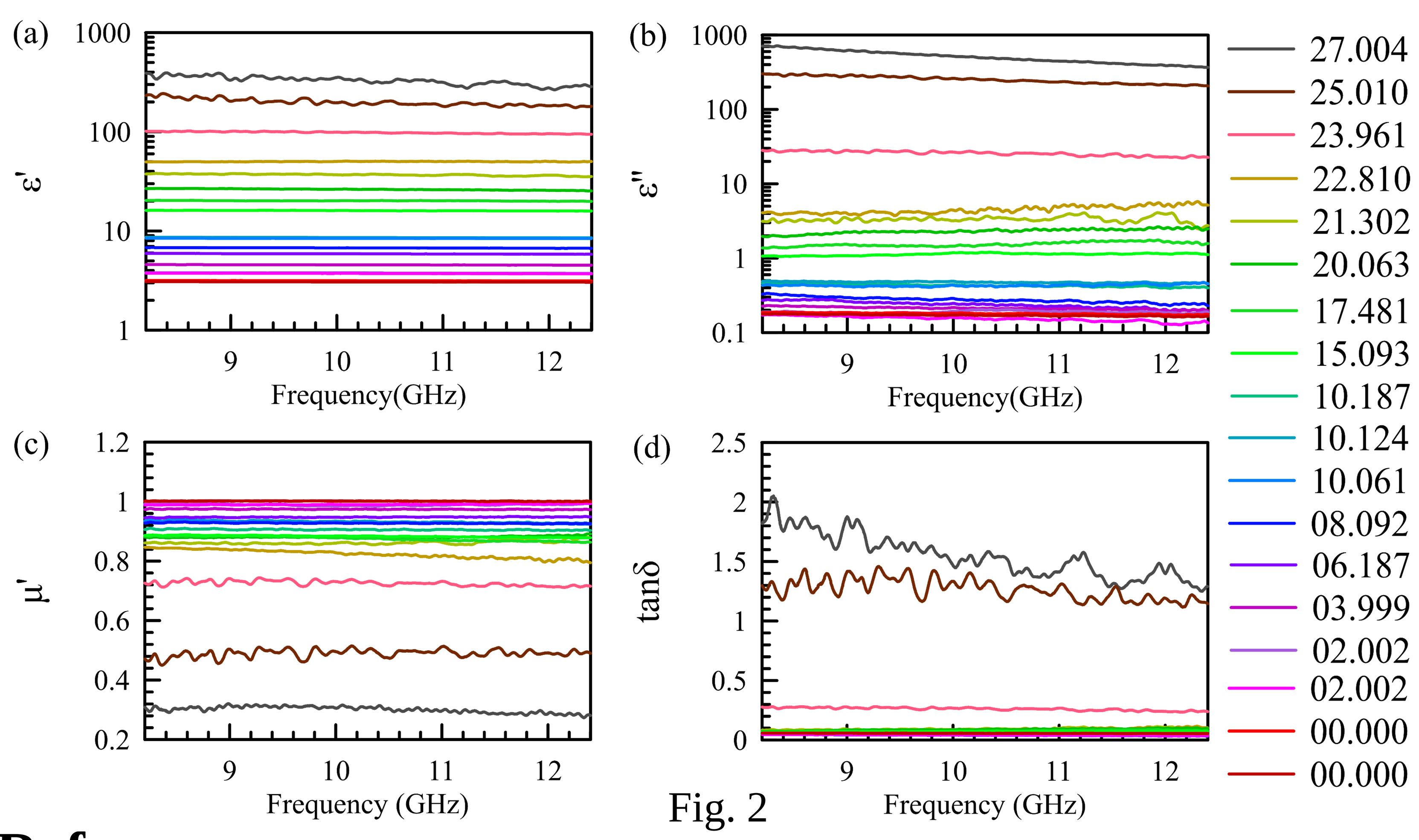

Fig. 2

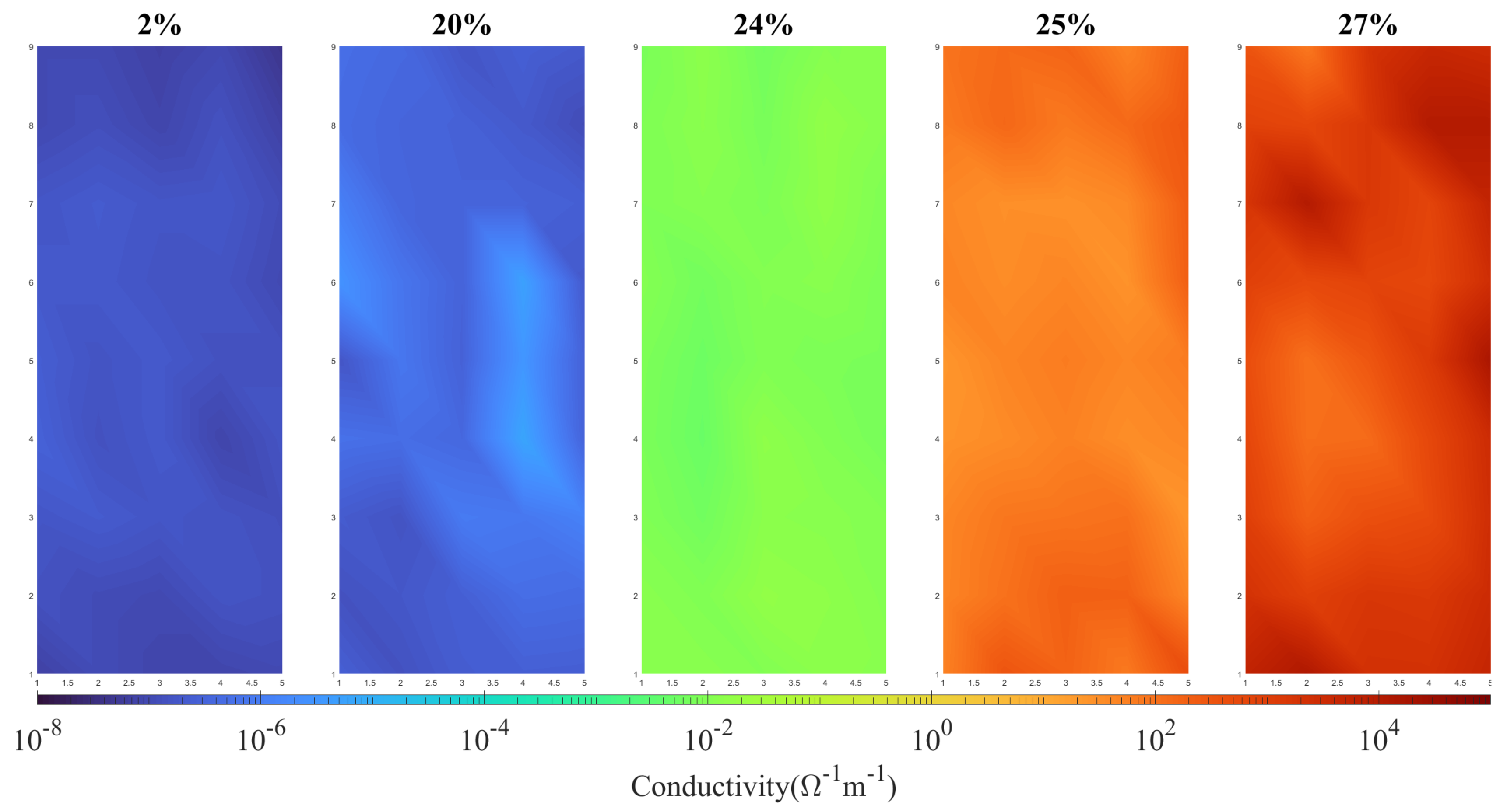

Fig. 3

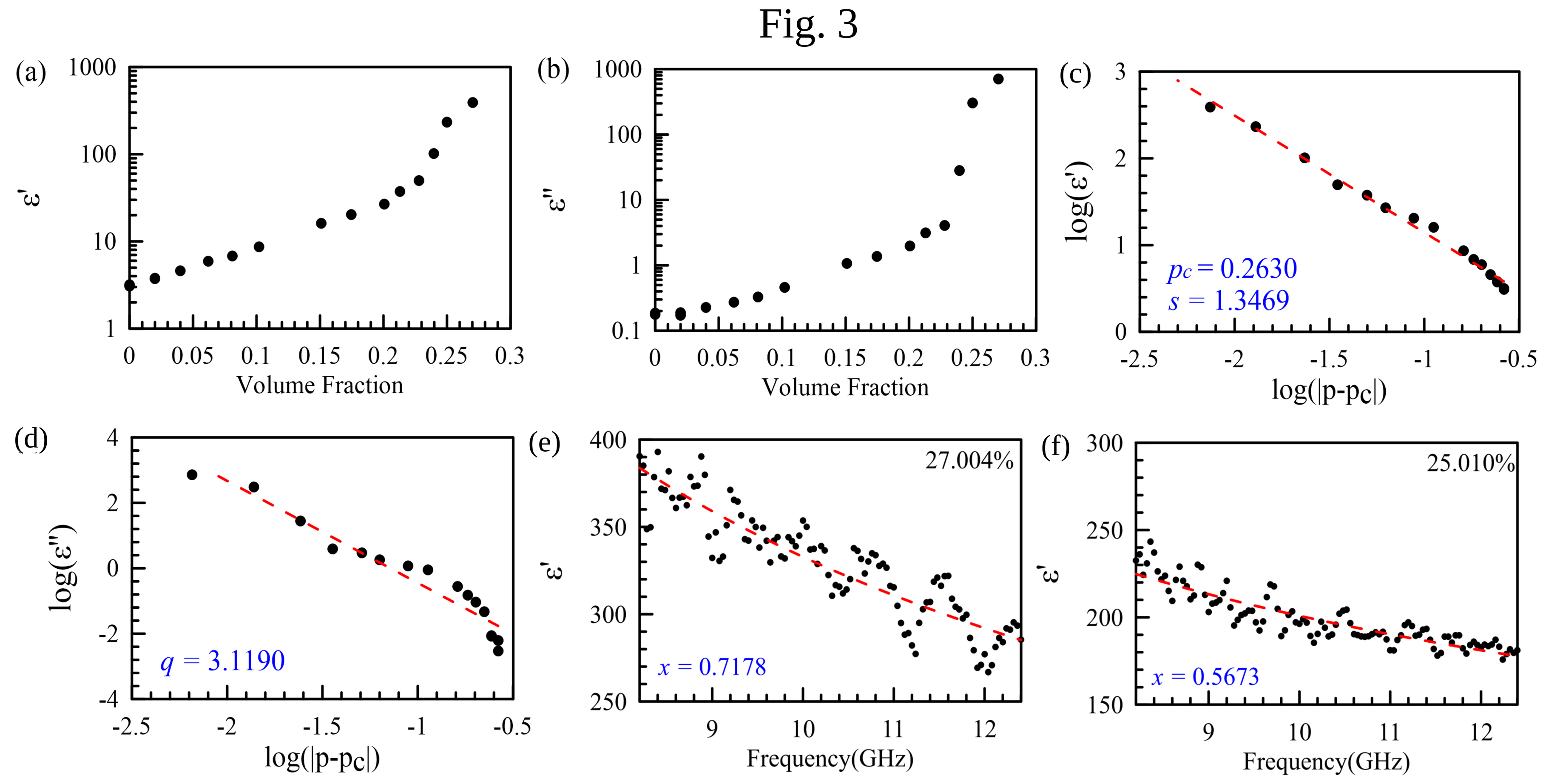

Fig. 4

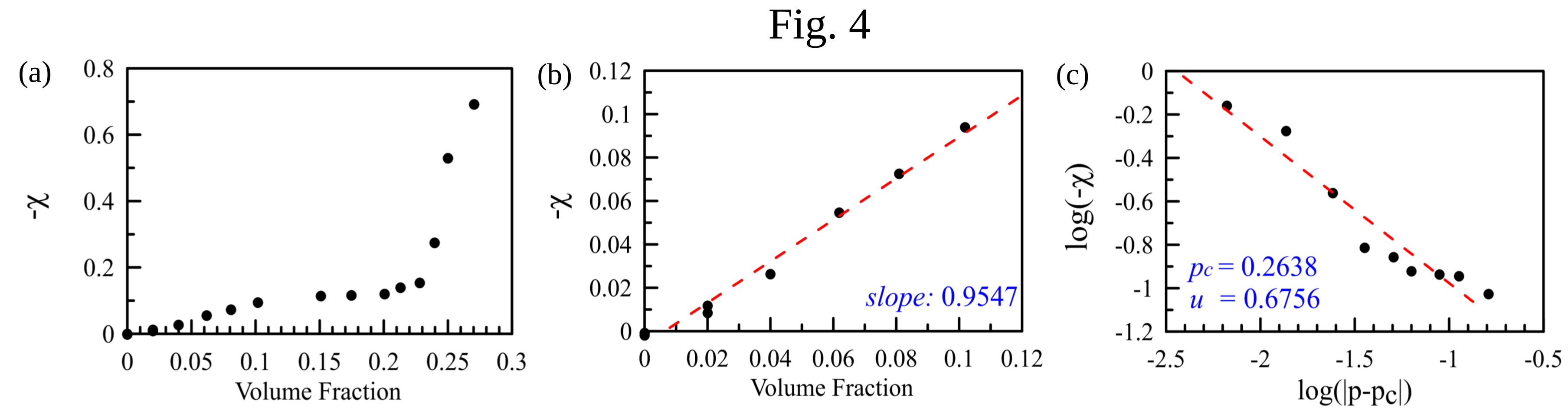

Fig. 5

Fig. 2 illustrate the frequency-dependent behaviour of complex permittivity, permeability, and the loss tangent for varying volume fractions. The complex permittivity exhibits minimal frequency dependence below 25%, and permeability shows no discernible frequency. According to the percolation theory, we have that

$$\varepsilon_r \sim |p-p_c|^{-s},\ \sigma_r \sim |p-p_c|^{-q},\ -\chi \sim |p-p_c|^{-u}.$$

The fitting result for ***s***, ***q*** and ***u*** was given in Fig. 4 and Fig. 5. Comparing Fig 3. with Fig 4(b)., they exhibit similar trends. The loss contributed mainly from the conductivity, and, therefore, in Fig 4(d)., the ε'' is subtracted by 0.18, which is the imaginary permittivity of pure epoxy. The result shows high consistency with the theory, which stated that $q \in [3,4]$. The fitting result of ***s*** falls outside of the theoretical value ($\boldsymbol{s} \sim 1$), however, multiple results of $\boldsymbol{s} > 1$ was reported. I think that the geometry shape of the filler might affect this critical exponent. Finally, the permeability is displayed in Fig 5. For simplicity, the negative susceptibility was presented. At low volume fraction, $-\chi$ follows $-\chi = -N\frac{\vec{m}}{\vec{H}_{inc}} = -C \cdot p$, where $C = \frac{2S^2}{PV}$ is the shape factor (S the surface, P the perimeter and V the volume). The theoretical value is in between 0.5 and 1.5, where my result lies in. For high volume fraction, $-\chi$ follows the power law. The theoretical value is in between 0.5 and 1, where my result exists.

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