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Battery-free Wireless Power from Ambient Wi-Fi via 3D-Printed Nanocomposites

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We use this protocol and it's working



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Abstract

The rapid deployment of renewable energy systems is reshaping global power infrastructure, yet life-cycle analyses reveal persistent carbon emissions associated with their manufacture and deployment. In parallel, the proliferation of wireless networks has saturated modern environments with ambient radiofrequency (RF) fields, which are increasingly recognized both as a pollutant and as an untapped energy resource. Here we report a 3D-printed CNT-Co metamaterial antenna that converts far-field RF radiation into usable electrical power with broadband efficiency. By integrating carbon nanotubes and cobalt nanoparticles into a UV-curable resin, we achieved strong conduction and magnetic losses that, when combined with a honeycomb metamaterial architecture, delivered absorption efficiencies up to 99.9% across dual frequency bands (3.35-4.59 GHz and 9.45-16.57 GHz). The system outperformed a commercial Wi-Fi antenna by factors of up to three under low input powers, maintained stable operation in ambient environments, and powered practical devices including LEDs, medical sensors, and wireless trackers. These results establish CNT-Co metamaterial antennas as a scalable platform for harvesting energy from the electromagnetic environment, opening new pathways toward sustainable, battery-free electronics.

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Guidelines

Preparation of CNT-Co UV-curable composites:

- Prepare a UV-curable epoxy resin by mixing 50 g neopentyl glycol diglycidyl ether and 20 g diphenyl(2,4,6-trimethyl benzoyl) phosphine oxide with 146 g bisphenol A epoxy diacrylate. Mechanically stir for 1 h.
- Add 2.5 g carbon nanotubes (CNTs), 31.3 g cobalt nanopowder and 50 g yttria-stabilized zirconia beads to the resin mixture.
- Achieve dispersion by high-speed stirring at 800 rpm for 3 h. After uniform dispersion, remove zirconia beads by filtration to yield the CNT-Co UV-curable composite.

3D printing of CNT-Co metamaterial antenna:

- Fabricate metamaterial units by layer-by-layer additive manufacturing using a Miicraft 100X 3D printer with the CNT-Co composite resin.
- Print each layer with a thickness of 0.05 mm and expose for 60 s.
- Assemble printed units into a 250 mm × 215 mm antenna using the same CNT-Co resin as a photopolymerizable adhesive.

Electromagnetic characterization of CNT-Co composites:

- Measure complex permittivity ($\epsilon = \epsilon' + j\epsilon''$) and permeability ($\mu = \mu' + j\mu''$) over 2–18 GHz using a coaxial airline fixture (Keysight 85051B) connected to a vector network analyzer (VNA; Keysight N5222B).
- Use toroidal samples (inner diameter 3.04 mm, outer diameter 7.00 mm, thickness 3.00 mm).
- Perform open-short-load calibration prior to measurement to ensure accuracy.
- Insert samples into the coaxial airline and connect to the VNA to acquire S11 parameters.
- Process data with Keysight N1500A software and extract permittivity and permeability values via Weir's reflection/transmission method.
- Calculate reflection loss across 2–18 GHz from the extracted parameters using standard transmission line equations:

$$ZL = Z0 \sqrt{(\mu_r/\epsilon_r) \tanh(j \omega / c \cdot \sqrt{\mu_r \epsilon_r} \cdot d)}$$

$$\text{and R.L. (dB)} = 20 \log |\Gamma|.$$

RF signal generation and LED demonstration:

- Use a Wi-Fi router transmitting at 2.45 GHz with an output power of 20 dBm as the RF source for proof-of-concept demonstrations.
- Monitor stability of RF energy harvesting (RFEH) with a nanovoltmeter (Keithley 2700s) under continuous RF exposure.
- Store harvested energy in supercapacitors and use it to drive an LED.

Rectifier fabrication:

- Connect the rectifier circuit as a load to the CNT-Co antenna to evaluate RF-to-DC conversion.
- Assemble rectifier from four Schottky diodes (BAT41), two 4.7 μ F ceramic capacitors, and include a matching network consisting of a 4.7 μ F capacitor and a 22 μ H inductor to match rectifier input impedance to antenna output impedance.
- Assemble and test rectifiers on breadboards for prototyping.

Operation of wearable monitoring device:

- Demonstrate powering a wearable health monitoring device integrating a pulse oximeter and heart rate sensor directly from the RFEH system.
- Connect rectified DC output to the device via alligator clips for direct operation under ambient Wi-Fi signals.

Materials

Neopentyl glycol diglycidyl ether; diphenyl(2,4,6-trimethyl benzoyl) phosphine oxide; bisphenol A epoxy diacrylate; carbon nanotubes (CNTs) — 2.5 g per batch example; cobalt nanopowder — 31.3 g per batch example; yttria-stabilized zirconia beads — 50 g per batch example; CNT-Co UV-curable composite resin (resulting product); Miicraft 100X 3D printer (used with CNT-Co resin); photopolymerizable adhesive (same CNT-Co resin used as adhesive); coaxial airline fixture (Keysight 85051B); vector network analyzer (VNA; Keysight N5222B); toroidal sample holders (inner diameter 3.04 mm, outer diameter 7.00 mm, thickness 3.00 mm); Keysight N1500A software; nanovoltmeter (Keithley 2700s); Wi-Fi router (2.45 GHz, 20 dBm output used as RF source); supercapacitors (for energy storage); light-emitting diode (LED); four Schottky diodes (BAT41, STMicroelectronics); two 4.7 μ F ceramic capacitors; additional 4.7 μ F capacitor (for matching network); 22 μ H inductor (for matching network); breadboards; alligator clips.

Before start

Prior to electromagnetic measurements perform open-short-load calibration of the VNA/coaxial fixture to ensure accuracy. Ensure toroidal samples are prepared to specified dimensions (inner diameter 3.04 mm, outer diameter 7.00 mm, thickness 3.00 mm). For composite preparation, have zirconia beads available for dispersion and a filtration setup to remove beads after mixing.

Preparation of CNT-Co UV-curable composites

- 1 Prepare a UV-curable epoxy resin by mixing 50 g neopentyl glycol diglycidyl ether and 20 g diphenyl(2,4,6-trimethyl benzoyl) phosphine oxide with 146 g bisphenol A epoxy diacrylate; mechanically stir the mixture for 1 h.
- 2 Add 2.5 g carbon nanotubes (CNTs), 31.3 g cobalt nanopowder and 50 g yttria-stabilized zirconia beads to the resin mixture.
- 3 Achieve dispersion by high-speed stirring at 800 rpm for 3 h.
- 4 After uniform dispersion, remove the zirconia beads by filtration to yield the CNT-Co UV-curable composite.

3D printing of CNT-Co metamaterial antenna

- 5 Fabricate metamaterial units by layer-by-layer additive manufacturing using a Miicraft 100X 3D printer with the CNT-Co composite resin.
- 6 Print each layer with a thickness of 0.05 mm and expose each layer for 60 s.
- 7 Assemble the printed units into a 250 mm × 215 mm antenna using the same CNT-Co resin as a photopolymerizable adhesive.

Electromagnetic characterization of CNT-Co composites

- 8 Measure the complex permittivity ($\epsilon = \epsilon' + j\epsilon''$) and permeability ($\mu = \mu' + j\mu''$) of the CNT-Co composite over 2–18 GHz using a coaxial airline fixture (Keysight 85051B) connected to a vector network analyzer (VNA; Keysight N5222B).
- 9 Use toroidal samples with an inner diameter of 3.04 mm, outer diameter of 7.00 mm and thickness of 3.00 mm for measurements.
- 10 Perform open-short-load calibration of the VNA/coaxial fixture prior to measurement to ensure accuracy.
- 11 Insert samples into the coaxial airline, connect to the VNA and acquire S11 parameters.

- 12 Process acquired data using Keysight N1500A software and extract permittivity and permeability values via Weir's reflection/transmission method.
- 13 Calculate reflection loss across 2–18 GHz from the extracted parameters using standard transmission line equations, e.g. $Z_L = Z_0 \sqrt{\mu_r/\epsilon_r} \tanh(j\omega/c \cdot \sqrt{\mu_r \epsilon_r} \cdot d)$ and $R.L. (dB) = 20 \log |\Gamma|$.

RF signal generation and LED demonstration

- 14 Use a Wi-Fi router transmitting at 2.45 GHz with an output power of 20 dBm as the RF source for proof-of-concept demonstrations.
- 15 Monitor the stability of the RF energy harvesting (RFEH) system in real time with a nanovoltmeter (Keithley 2700s) under continuous RF exposure.
- 16 Store harvested energy in supercapacitors and use it to drive a light-emitting diode (LED).

Rectifier fabrication

- 17 Connect the rectifier circuit as a load to the CNT-Co antenna to evaluate RF-to-DC conversion.
- 18 Assemble the rectifier from four Schottky diodes (BAT41, STMicroelectronics) and two 4.7 μ F ceramic capacitors.
- 19 Include a matching network consisting of a 4.7 μ F capacitor and a 22 μ H inductor to match the rectifier input impedance to the antenna output impedance and maximize power transfer.
- 20 Assemble and test rectifiers on breadboards for prototyping and ease of modification.

Operation of wearable monitoring device

- 21 Power a wearable health monitoring device integrating a pulse oximeter and heart rate sensor directly from the RFEH system to demonstrate real-world applicability.
- 22 Connect the rectified DC output to the wearable device via alligator clips to enable direct operation under ambient Wi-Fi signals.

