Abstract: A pinch harmonic (or guitar harmonic) is a musical note produced by lightly pressing the thumb of the picking hand upon the string immediately after it is picked [J. Chem. Educ. 84, 1287 (2007)]. This technique turns off the fundamental and all overtones except those with a node at that location. Here we present a terahertz analogue of pinch harmonics, whereby a metallic nano rod placed at a harmonic node on a terahertz nanoresonator suppresses the fundamental mode, making the higher harmonics dominant. Strikingly, a skin depth-wide nano rod placed at the mid-point turns off all resonances. Our work demonstrates that terahertz electromagnetic waves can be tailored by nanoparticles strategically positioned, paving important path towards terahertz switching and detection applications.

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OCIS codes: (300.6495) Spectroscopy, terahertz; (310.6628) Subwavelength structures, nanostructures; (300.6380) Spectroscopy, modulation.

References and links


1. Introduction

Propagation of electromagnetic waves is not disturbed in general by an obstacle of size much smaller than the wavelength. This wave nature makes it difficult to detect nano-size particles using terahertz (THz) waves. The situation changes drastically, however, when the particle interacts with the resonant modes of electromagnetic waves. Multiple reflections accompanying resonance increase effective interactions between particle and wave. Recently, optical antennas with a narrow mid-gap have received much attention regarding the field enhancement [1–4], nanoparticle detection [5–7], and pattern-tuning ability [8–10]. However, particles or molecules should be placed only at the gap region, limiting the functionalities of these positive antennas. On the other hand, negative, slot antennas enhance electric field over
the whole aperture [11–14], so that the position of the particles becomes an important controlling parameter.

![Image](image.png)

Fig. 1. (a) Nano rod placed on the top of THz nanoresonator generates pinch harmonic behaviors, analogous to a finger slightly touching a guitar string. The p-polarized terahertz pulses with polarization perpendicular to the long axis of the rectangle are normally incident on the sample. (b) (top) An SEM picture of a platinum (Pt) nano rod with a length $l_2 = 1 \mu m$, a width $w_2 = 600 \text{ nm}$, and a thickness $t_2 = 400 \text{ nm}$, located at the 1:2 position on a THz nanoresonator with $l_1 = 300 \mu m$ and $w_1 = 120 \text{ nm}$. At the bottom, enlarged SEM images of the same nano rod (left) and a smaller nano rod (right) with $l_2 = 1 \mu m$, $w_2 = 250 \text{ nm}$, and $t_2 = 250 \text{ nm}$.

In this work, we demonstrate control of the THz electromagnetic wave transmission by metallic nano rods with volumes far smaller than $(\lambda/1,000)^3$, placed on top of the slot antenna (Fig. 1(a)). Larger nano rod, constituting a hard boundary, creates new fundamental modes on each side of the antenna. A smaller nano rod of skin-depth dimension allows only those modes with nodes on that particular position, disturbing the overall transmission curve even more than larger rods. Counter-intuitively, the smallest nano rod we used blocks all transmission when placed at mid-point. The ability to control THz transmission with smallest volume offers a great opportunity for developing high-speed and high performance devices.

2. Experiments

For an ordinary pluck of a string, the resulting vibration is a superposition of standing waves: the first few modes ($n = 1, 2, \text{ and } 3$) are illustrated in Fig. 2(a, left). If we wish to have higher harmonic modes, we firmly place our finger at, say, the 1:2 position along the string, generating two different fundamental modes at each side, suppressing the original fundamental mode completely (Fig. 2(a, middle)). When the finger lightly touches the same position on the string, the third harmonic becomes the dominant mode, suppressing both the original fundamental mode and the new fundamental mode of the long side (Fig. 2(a, right)). This technique is called 'pinch harmonics', being useful for fine-tuning a guitar. The concept of terahertz pinch harmonics is when the string is replaced by the extreme-ratio nano slot antenna and the finger by nano rods.
Fig. 2. (a) Fundamental mode and higher harmonics modes \((n = 2\) and \(3\)) on a string (left). Two isolated fundamental modes on each side are created by firmly placing a finger located at the 1:2 position (middle). Dominant third harmonic mode by lightly touching the string at the same position (right). At the bottom, they are mimicked by THz nanoresonators without nano rod (left), with a larger nano rod at the 1:2 position (middle), and with a smaller nano rod (right), respectively. (b) Fourier-transformed transmittance spectra of single THz nanoresonators without a nano rod, with the larger and smaller Pt nano rods at the 1:2 position, using terahertz time-domain spectroscopy. (c) The square of \(x\)-directional electric field near the exit of nanoresonators \((l_1 = 10 \text{ µm} \text{ and } w_1 = 20 \text{ nm})\) without nano rod (top), with a 60 nm-wide larger nano rod, and with a 20 nm-wide smaller nano rod at the fundamental frequency (left) are calculated by FDTD simulations. Electric field patterns at the third harmonic frequency for each case are also shown in right side.

Shown in Fig. 2(b) are transmission spectra of vertically-aligned single nanoresonators in the frequency range from 0.1 THz to 1.0 THz using THz time domain spectroscopy [15, 16]. The nanoresonators, patterned by focused ion beam, have dimensions of \(l_1 = 300 \text{ µm} \text{ and } w_1 = 120 \text{ nm}\) on gold film of 60 nm thickness deposited onto a 2 µm-thick SiN/SiO\(_2\) substrate, inducing strong electric field enhancement of more than 1,000 inside the aperture at the fundamental resonance of 0.26 THz [17–21]. We prepare two nano rods by platinum (Pt) deposition method using focused ion beam. The larger rod has a dimension of \(l_2 = 1 \text{ µm}, w_2 = 600 \text{ nm}, \text{ and } t_2 = 400 \text{ nm}\), while the smaller one has \(l_2 = 1 \text{ µm}, w_2 = 250 \text{ nm}, \text{ and } t_2 = 250 \text{ nm}\) so that the width and thickness are about the skin depth of 280 nm at 0.4 THz [22, 23] (Fig. 1(b)). When we put the larger nano rod at the 1:2 position, the resonance peak is pushed to about 0.34 THz and 0.78 THz caused by the new nanoresonators with the length of 200 µm and 100 µm. For the smaller nano rod placed at 1:2 position, indeed the third harmonic resonance of 0.78 THz dominates in the pinch harmonic sense. Despite this dominance, the original fundamental mode still exists with a high frequency shoulder mostly likely from the fundamental mode of the long side. This is most likely because the disturbance is located not at the maximum of the original fundamental mode implying that when we put the nano rod at the 1:1 position, even the remaining fundamental may completely disappear.

For simulate pinch harmonics by Pt nano rods, we perform three-dimensional finite-difference time-domain (FDTD) analysis using Drude model [24–26] assuming a rectangular hole with a length of 10 µm and a width of 20 nm in a thin gold film with a thickness of 20 nm. Dimensions of our nanoresonators and nano rods are scaled down for optimization of our simulations. Especially, to extract the same sub-skin depth physics in the simulations, considering the gold and Pt skin depths, we apply different scaling factors to the width and
thickness of the nanoresonators and nano rods. In Fig. 2(c, left), the square of x-directional electric field patterns near the exit of nanoresonator without nano rod (top), with a 60 nm-wide larger nano rod (middle), and with a 20 nm-wide smaller nano rod (bottom) at 1:2 position are plotted at the fundamental mode frequency. Figure 2(c, right) shows the electric field patterns of the same parameter nanoresonators, as used in the fundamental mode case, at the third harmonic frequency. The third harmonic strength is slightly enhanced even as the first mode is substantially suppressed at the rod-size below the skin depth ($\delta_{Pt} \approx 30$ nm at $\lambda = 10 \mu m$ [22, 23]), which confirms THz pinch harmonic behaviors of our sample structures.

![Fig. 3. (a) Schematics for THz pinch harmonics by a single nano rod at the 1:1 position, consisting of THz nanoresonator without nano rod (top), with a larger nano rod (bottom, left), and with a smaller nano rod (bottom, right). (b) Transmittance spectra of a 300 $\mu m$-long nanoresonators without nano rods, with the two same parameter nano rods used in Fig. 2(b) at 1:1 position.](image)

When we place the nano rods at the 1:1 position (Fig. 3(a)), profound changes are expected to take place in the transmission spectra. The larger nano rod with 600 nm width at the mid-point turns off the fundamental as well as $n = 3$ modes, and generates the new resonance ($n=2$ mode) at twice larger than the fundamental resonance frequency (Fig. 3(a) (bottom, left)). For the smaller nano rod, even the $n=2$ mode, which can survive because it has node in the middle, do not radiate to the far-field because the positive and negative parts cancel (Fig. 3(a) (bottom, right)): $E_{near} = \frac{e^{ikR}}{i\lambda R} \int E_{near} dA$ according to Kirchhoff formalism, where $E_{near}$ is the electric field inside the aperture, $A$ the aperture area, and $R$ the distance from the aperture to the detector. Figure 3(b) shows transmittance spectra, measured for the same $l_1 = 300 \mu m$ nanoresonators without nano rods, with the two same parameter nano rods as used in Fig. 2(b), and with new smaller nano rods. Indeed, the fundamental and third harmonic modes are almost completely suppressed by the 250 nm-width nano rod although a small resonance is visible at the $n=2$ spectral position.

### 3. Discussion

For better insight into THz pinch harmonics, a microscopic diffraction model with a gold nano rod fit into the aperture is carried out, as shown in Fig. 4(a, left). In view of microscopic diffraction of light [27], we consider the simplified model as shown in Fig. 4(a, right) fitting the nano rod with a width $s$ at the location of $P_2$. When light passes through a long rectangular aperture at the normal incidence, resonance of light inside the hole arises due to the constructive build-up of reflected components of electromagnetic waves by the edge of rectangle. When the nano rod with the sub-skin depth dimension is placed inside the aperture, it causes partial reflection and transmission of light. The partially transmitted light gets reflected at the other edge ($P_3$) and destructively interferes with the reflected light by the nano rod, resulting in THz pinch harmonics.
Fig. 4. (a) (left) Simplified model fitting a gold nano rod (width $s$) at $d_1, d_2$ position inside the THz nanoresonator. (right) Microscopic diffraction processes at the nano rod and two edges of the aperture for the normal incidence of THz wave are illustrated in the cut plane. (b) Calculated transmitted field amplitude spectra depending on nano rod width at 1:2 position (c) The same as (b) but for a nano rod at 1:1 position. The unit of frequency in $x$-axis is the original fundamental resonance frequency, $f_c = c / 2l$.

We assume that scattered light with electric field amplitude $E_0$ is injected at $P_1$. Then the subsequent electric field inside the rectangle with the length $d_1 + d_2$ due to the multiple reflections is described by

$$
E_{r_1}^{P_1 \rightarrow P_1} = E_0 e^{ik_y y} + E_x e^{ik (d_2 - y)}, \quad \text{for} \quad 0 \leq y \leq d_1 \quad (\text{region 1}),
$$

$$
E_{r_2}^{P_1 \rightarrow P_1} = E_0 e^{ik (y - d_1)} + E_x e^{ik (d_1 - y)}, \quad \text{for} \quad d_1 \leq y \leq d_1 + d_2 \quad (\text{region 2}),
$$

$$
E_{r}^{P_1 \rightarrow P_1} = E_{r_1}^{P_1 \rightarrow P_1} + E_{r_2}^{P_1 \rightarrow P_1}.
$$

If we denote $E_1^m$ to be the amplitude of light injected at $P_1$ after $m$-times reflection, we find that

$$
E_1 = E_0^0 + E_1^1 + \cdots + \frac{E_0^m}{1 - \eta}, \quad \text{where} \quad \eta = e^{i2\delta d_1} \left( \beta r + \frac{t^2 r e^{i2d_2}}{1 - \beta r e^{i2d_2}} \right),
$$

$$
E_2 = E_1 e^{ik d_2} \left( \beta + \frac{t^2 r e^{i2d_2}}{1 - \beta r e^{i2d_2}} \right), \quad E_3 = E_2 e^{ik(d_1 + d_2)} / \beta r e^{i2d_2}, \quad E_4 = E_2 e^{i(d_1 + d_2)} / \beta r e^{i2d_2},
$$

$$

\text{where} \quad t = e^{i\delta} \quad \text{is the transmission coefficient through the nano rod with the width $s$,} \quad \delta \quad \text{the skindepth of gold,} \quad \beta = -\sqrt{1 - t^2} \quad \text{the reflection coefficient at the nano rod, and} \quad r \quad \text{the reflection coefficient} \quad (= 0.99) \quad \text{at two edges. Since light is also injected via diffraction at the other edge} \quad P_3, \quad \text{the total electric field is given by} \quad E_{tot} = E_{r}^{P_1 \rightarrow P_1} + E_{r_3}^{P_3 \rightarrow P_1} \quad \text{Diffractions at the nano rod with}
\]
sub-skin depth dimensions can be ignored [23, 28–30]. The magnitude of resonant transmitted field, in the Kirchhoff sense, is given by \( \int_{0}^{d_{1}+d_{2}} E_{\text{tot}} \, dx \).

Figure 4(b) and 4(c) shows transmitted spectra with the nano rods at the 1:2 and 1:1 positions, respectively, obtained from our microscopic diffraction model. At an \( s \) of around 0.3\( \delta \), we obtain qualitatively similar results with experiments shown in Fig. 2(b) and 3(b). However, the dimension of the nano rod in experiments to produce pinch harmonic effect is much larger, most likely because reflection by a nano rod sitting on top of the aperture would be much smaller than that by a nano rod fit into the aperture.

4. Conclusion

We showed that a single nano rod placed on THz nanoresonator greatly influences its spectrum, selecting one specific resonance analogous to pinch harmonics. Strikingly, the smallest nano rod with the skin-depth dimension at the 1:1 position on our slot antenna shuts off all the resonances up to 80%. THz pinch harmonics provides new physical origin for controlling far-field transmission without the need to change dielectric property of the whole substrate under the slot, which limits speed [31–33]. Moreover, the extreme sensitivity to nano rod dimensions and positions promises a new scheme for nanoparticles detection.

Acknowledgments

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (MEST) (SRC, No:R11-2008-095-01000-0) (No:2010-0029648, 2010-0028713, 2011-0019170, 2011-0020209), KICOS (GRL, K20815000003), and Hi Seoul Science / Humanities Fellowship from Seoul Scholarship Foundation.