# Experimental confirmation of backscattering enhancement induced by a photonic jet

Alexander Heifetz[a)]
*Biophotonics Laboratory, Department of Biomedical Engineering, Northwestern University, Evanston, Illinois 60208*

Kevin Huang
*Department of Electrical Engineering and Computer Science, Northwestern University, Evanston, Illinois 60208*

Alan V. Sahakian and Xu Li
*Department of Biomedical Engineering, Northwestern University, Evanston, Illinois 60208 and Department of Electrical Engineering and Computer Science, Northwestern University, Evanston, Illinois 60208*

Allen Taflove
*Department of Electrical Engineering and Computer Science, Northwestern University, Evanston, Illinois 60208*

Vadim Backman
*Biophotonics Laboratory, Department of Biomedical Engineering, Northwestern University, Evanston, Illinois 60208*

(Received 8 August 2006; accepted 16 October 2006; published online 30 November 2006)

The authors report experimental confirmation of backscattering enhancement induced by a photonic jet emerging from a dielectric sphere, a phenomenon recently predicted by theoretical solutions of Maxwell's equations. To permit relatively straightforward laboratory measurements at microwave frequencies rather than visible light, they appropriately scaled the original conceptual dimensions of the dielectric microsphere and its adjacent perturbing nanoparticle (located within the microsphere's photonic jet). Their experiments verified the existence of enhanced position-dependent backscattering perturbations by the adjacent particle. Their measured backscattering perturbations agreed well with prior theory and with additional finite-difference time-domain computational models of the complete microwave test geometry. © *2006 American Institute of Physics*.
[DOI: 10.1063/1.2398907]

Several recent papers[1–5] have implemented Mie expansion[6] and/or finite-difference time-domain[7] (FDTD) computational solutions of Maxwell's equations to predict the existence of a subwavelength-waist photonic jet that emerges from the far side of a plane-wave-illuminated circular dielectric cylinder or sphere of micron dimensions, and an associated enhanced backscattering by nanoparticles located within the photonic jet.[1,2,5] The latter findings indicate that the presence of a nanoparticle within a photonic jet can greatly perturb the backscattering of the microsphere, despite the fact that the nanoparticle diameter might be less than 1/100 that of the microsphere. In fact, this perturbation could be many orders of magnitude greater than the intrinsic backscattering of the isolated nanoparticle.

In this letter, we report an experimental confirmation of the photonic jet for a dielectric sphere and its associated enhanced backscattering phenomenon. To facilitate the measurements, we scaled upward the originally reported diameter of the dielectric sphere from the micron scale illuminated by visible light to the centimeter scale illuminated by microwaves. Specifically, we illuminated a 7.62 cm diameter acrylic sphere (polymethylmethacrylate, permittivity $\varepsilon = 2.57 + j0.0082$) at 30 GHz ($\lambda_0 = 1$ cm) to generate a photonic jet.[8] When small spherical metal particles of various diameters from 1 to 3 mm ($0.1\lambda_0 - 0.3\lambda_0$) were introduced into the jet, we measured superenhanced position-dependent perturbations of the overall backscattered intensity. These perturbations were in good agreement with prior theory and an additional FDTD computational solution of Maxwell's equations that modeled the complete microwave test geometry.

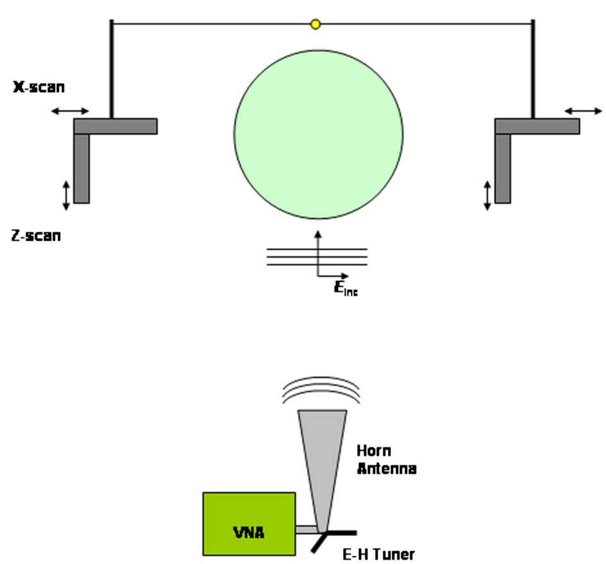


FIG. 1. (Color online) Schematic diagram of the experimental setup.

[a)]Electronic mail: a-heifetz@northwestern.edu

 

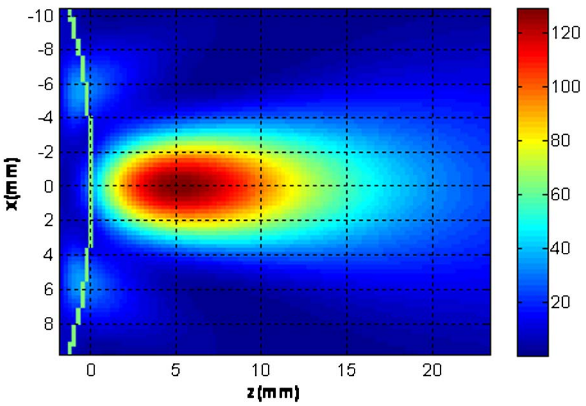


FIG. 2. (Color online) Visualization of the FDTD-computed microwave jet produced in the experimental setup of Fig. 1 with a 7.62 cm acrylic sphere illuminated by $x$ polarized antenna radiation at 30 GHz. The zero point of the vertical ($z$) axis is at the top surface of the acrylic sphere. The jet's intensity maximum is 130 at $z$=5.25 mm, and the jet's waist is $0.8\lambda_0$.

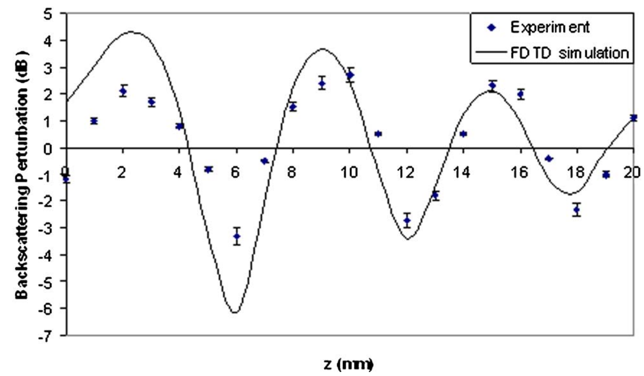


FIG. 3. (Color online) Measured and FDTD-calculated backscattering perturbation caused by the 1 mm metal particle scanned vertically along the center line of the microwave jet (log-linear plot). $z$ is the distance between the top surface of the acrylic sphere and the surface of the metal particle.

Figure 1 illustrates a schematic diagram of the experimental arrangement. We used an Agilent 8722ES 40-GHz-bandwidth vector network analyzer (VNA) to generate a monochromatic 30 GHz illumination and to measure the backscattered response. A WR28-to-WR90 waveguide transition was used as a horn antenna with an aperture size of $2.3\times 1$ cm$^2$. This antenna was pointed upward avoid to reflections from the surface of the optical table. Using a Styrofoam sheet holder, the acrylic sphere was positioned above the antenna in its far field at a separation of 21 cm. The far field pattern of the antenna[9] corresponds to distances from the antenna greater than $2D^2/\lambda_0=10.6$ cm, where $D=2.3$ cm is the largest dimension of the antenna aperture. Therefore, one can assume that the sphere was located in the far field of the antenna radiation.

The backscattered intensity was determined by measuring $S_{11}$ with the VNA. An *E-H* tuner was used to null out intrinsic reflections in the system,[10] especially due to the Styrofoam holder for the acrylic sphere. After nulling the system without the acrylic sphere present, we measured $S_{11}\cong -60$ dB. This noise floor was found to be stable during the duration of the measurements. After the acrylic sphere was placed in position above the horn antenna, we measured $S_{11}\cong -51.5$ dB. This level was also found to be stable during the complete series of measurements.

We obtained metal spheres of diameters 1, 1.5, 2, 2.5, and 3 mm ($0.1\lambda_0$, $0.15\lambda_0$, $0.2\lambda_0$, $0.25\lambda_0$, and $0.3\lambda_0$, respectively), and drilled small holes in each particle to permit its mounting on an 80 $\mu$m diameter nylon fiber (Invisible Thread). The nylon fiber supporting a metal particle was stretched tightly above the acrylic sphere, with the ends of the fiber attached to a pair of translation stages (Zaber Technologies) to permit computer-controlled positioning of the particle in three dimensions. Particle positions could be altered in 1 mm ($0.1\lambda_0$) spatial increments while automatically measuring the $S_{11}$ perturbations. Subsequently, we measured the maximum jet-facilitated $S_{11}$ perturbation caused by the nylon fiber alone to be approximately 0.6 dB, which turned out to be small in comparison with the $S_{11}$ perturbations of any of the metal particles. We also determined that none of the particles could be detected by the VNA when the acrylic sphere generating the microwave jet was taken out of the setup.

Figure 2 is a visualization of the $x$-polarized microwave photonic jet for this experimental arrangement (including the horn antenna source and the nylon support fiber) as calculated using a single-grid, three-dimensional FDTD model with a uniform $\lambda_0/40$ spatial resolution and perfectly matched layer absorbing outer boundary conditions.[7] The peak intensity of the microwave jet is 130 times that of the incident wave at a point $z$=5.25 mm from the back surface of the sphere. Here, the full width at half maximum waist of the jet is $0.5\lambda_0$, or $0.8\lambda_0$ as measured between $1/e^2$ intensity points.

Figure 3 presents our results for the measured and FDTD-calculated $S_{11}$ perturbations caused by the 1 mm ($0.1\lambda_0$) metal particle located along the center line of the microwave jet as a function of the distance $z$ of the particle from the top surface of the acrylic sphere. Here, we define the backscattered intensity perturbation as $\Delta S=S_{\mu+\nu}/S_{\mu}$, where $S_{\mu+\nu}$ is the $S_{11}$ due to the backscattering from the combined system of the acrylic sphere and the metal particle, and $S_{\mu}$ is the $S_{11}$ due to backscattering from the dielectric sphere alone. The error bars in Fig. 3 (as well as in Figs. 4 and 5) correspond to the measurement estimation errors of the VNA. We observe a relatively good agreement between the measurements and the FDTD calculations.

From Fig. 3, we see that $\Delta S$ varies approximately sinusoidally as a function of $z$ with a spatial period of about 6 mm. (Backscattering periodicity of a pair of equal-diameter conducting spheres has been studied in 11 and 12.) We have verified numerically as well as experimentally that this spatial period is independent of the size of the metal particle and the acrylic sphere (confirming the latter by repeating the experiment with a 10-cm-diameter acrylic sphere).

The experimentally measured amplitude of the backscattering perturbation $\Delta S$ for the 1 mm metal particle in Fig. 3 is about 3 dB. In other words, the backscattering from the acrylic sphere appeared to double (or halve) when the metal particle was appropriately positioned in the microwave jet. This means that the effective backscattering cross section of the small ($0.1\lambda_0$) metal particle was superenhanced by the microwave jet to be comparable to that of the much larger ($8\lambda_0$) dielectric sphere. We also note that the measured decibel reduction in the backscattered signal at $z$=6 mm was larger than the increase at either $z$=3 or 9 mm.

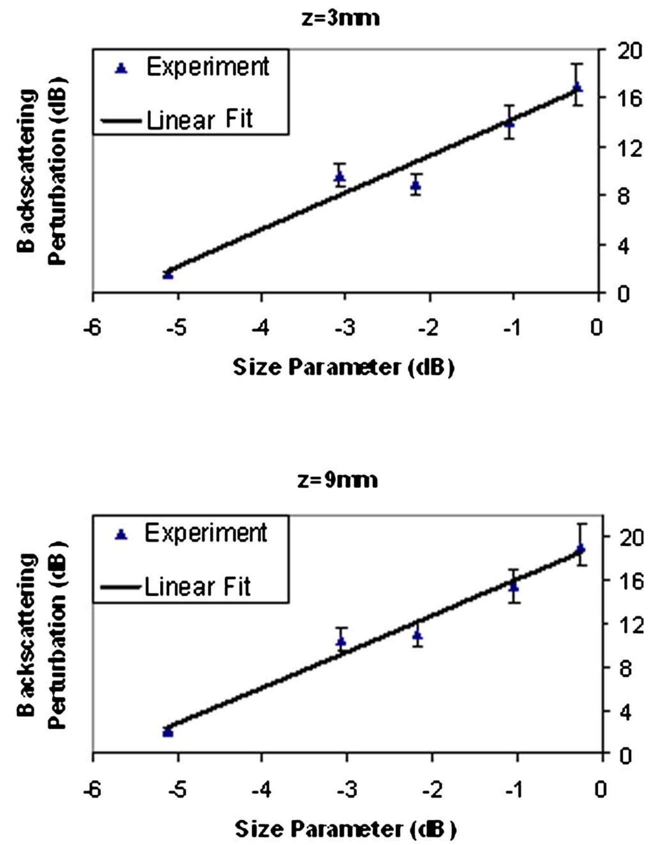


FIG. 4. (Color online) Measured dependence of the backscattering enhancement on the size parameter of the metal particle (log-log plot). At $z=3$ mm, a linear fit with $R^2=0.96$ has a slope $m=3.04$. At $z=9$ mm, a linear fit with $R^2=0.98$ has a slope $m=3.34$.

This is because the location of the metal particle at $z=6$ mm is near the highest intensity spot of the jet at $z=5.25$ mm (see Fig. 2).

We next consider the dependence of the backscattered perturbation $\Delta S$ on the size parameter $\alpha=\pi d/\lambda_0$ of the metal particles at various positions $z$ within the center of the microwave jet. Figure 4 displays log-log plots of the measured $\Delta S$ vs $\alpha$ at $z=3$ mm and $z=9$ mm, the locations of the first two peaks of the oscillations of $\Delta S(z)$ in Fig. 3. At $z=3$ mm, an EXCEL linear fit with $R^2=0.96$ has the slope $m=3.04$. ($R^2$ is the coefficient of determination, an indicator from 0 to 1 that reveals how closely the estimated linear trend corresponds to the actual data.) At $z=9$ mm, a linear fit with $R^2=0.98$ has the slope $m=3.34$. These experimental results are consistent with our earlier theoretical predictions of a third-order dependence of the superenhanced backscattering on the size parameter of the nanoparticle within the photonic jet.[5]

Finally, in order to estimate the lateral spatial resolution of particle detection by the microwave jet, we scanned the 1 mm metal particle along the $x$ direction in the $E$-field plane at a fixed distance $z=9$ mm from the top surface of the acrylic sphere. Figure 5 presents the experimental backscattered intensity perturbation data for this case along with the corresponding FDTD numerical simulation results. Relatively good agreement is again observed. The width of the scan can be estimated from the experimental data to be approximately equal to $\lambda_0$, which is larger than the jet waist of $0.8\lambda_0$ estimated from Fig. 2. We believe that the difference arose from the $0.1\lambda_0$ diameter of the metal probe particle, which resulted in a slight widening of the scan.

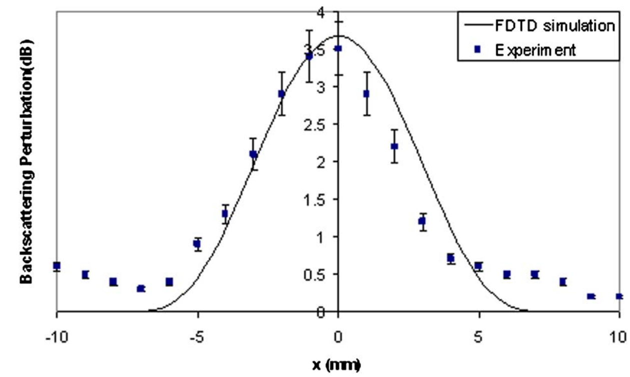


FIG. 5. (Color online) Measured and FDTD-calculated backscattering perturbation caused by the 1 mm metal particle scanned laterally across the microwave jet at a fixed distance $z=9$ mm from the top surface of the acrylic sphere (log-linear plot).

To summarize, we have reported an experimental confirmation of the photonic jet for a dielectric sphere and its associated enhanced backscattering phenomenon, whose existence was recently predicted based on analytical and computational solutions of Maxwell's equations. To facilitate the measurements, we scaled upward the originally reported dimensions of the dielectric sphere from the micron scale illuminated by visible light to the centimeter scale illuminated by microwaves. Specifically, we illuminated a 7.62-cm-diameter acrylic sphere at 30 GHz ($\lambda_0=1$ cm) to generate a subwavelength-waist photonic jet emerging from the far side of the sphere. When small spherical metal particles of various diameters from 1 to 3 mm ($0.1\lambda_0-0.3\lambda_0$) were introduced into the jet, we observed enhanced position-dependent perturbations of the overall backscattered intensity that agreed well with prior theory and with an additional FDTD computational model of the complete microwave geometry.

The authors would like to thank Alexey Kromin and Bo Liu for their help with the experiment. This work was supported by NSF Grant No. BES-0522639, NIH Grant No. R01EB003682, and NSF TeraGrid Grant No. MCB040062N.

[1] Z. Chen, A. Taflove, and V. Backman, Opt. Express **12**, 1214 (2004).
[2] X. Li, Z. Chen, A. Taflove, and V. Backman, Opt. Express **13**, 526 (2005).
[3] S. Lecler, Y. Takakura, and P. Meyrueis, Opt. Lett. **30**, 2641 (2005).
[4] A. V. Itagi and W. A. Challener, J. Opt. Soc. Am. A **22**, 2847 (2005).
[5] Z. Chen, X. Li, A. Taflove, and V. Backman, Opt. Lett. **31**, 196 (2006).
[6] H. C. van de Hulst, *Light Scattering by Small Particles* (Dover, Mineola, NY, 1981), pp. 114–130.
[7] A. Taflove and S. C. Hagness, *Computational Electrodynamics: The Finite-Difference Time-Domain Method*, 3rd ed. (Artech House, Boston, 2005), pp. 273–328.
[8] *Dielectric Materials and Applications*, edited by A. R. Von Hippel (Artech House, Boston, 1995), p. 334.
[9] C. A. Balanis, *Advanced Engineering Electromagnetics* (Wiley, New York, 1989), p. 282.
[10] *Principles of Microwave Circuits*, edited by C. G. Montgomery, R. H. Dicke, and E. M. Purcell (McGraw-Hill, New York, 1948), pp. 179–186.
[11] B. Peterson and S. Ström, Phys. Rev. D **8**, 3661 (1973).
[12] C. Liang and Y. T. Lo, Radio Sci. **2**, 1481 (1967).