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Observation of Wakefield Suppression in a Photonic Band Gap Accelerator Structure

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We report experimental observation of higher order mode (HOM) wakefield suppression in a room-temperature traveling-wave photonic band gap (PBG) accelerating structure at 11.700 GHz. It has been long recognized that PBG structures have potential for reducing long-range wakefields in accelerators. The first ever demonstration of acceleration in a room-temperature PBG structure was conducted in 2005. Since then, the importance of PBG accelerator research has been recognized by many institutions. However, the full experimental characterization of the wakefield spectrum and demonstration of wakefield suppression when the accelerating structure is excited by an electron beam has not been performed to date. We conducted an experiment at the Argonne Wakefield Accelerator (AWA) test facility and observed wakefields excited by a single high charge electron bunch when it passes through a PBG accelerator structure. Excellent HOM suppression properties of the PBG accelerator were demonstrated in the beam test.

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Modern day accelerator science produces major impact in many fields. The reach of accelerators now extends beyond pure discovery science and spans almost all aspects of our lives, meeting the needs of medicine, energy, environment, defense, and security. A recent Accelerator Task Force report [1] suggested that more accelerator R & D should be directed towards generating higher intensities, higher power, greater reliability and greater efficiency for accelerators, while making accelerators more compact and less costly. One enabler to more cost-efficient and compact machines is the ability to achieve high accelerating gradients, which naturally calls for higher frequency accelerating structures. Unfortunately, at higher frequencies higher order modes (HOMs) get excited by a high current electron beam that propagates through the accelerating structure. HOMs, in turn, interact with the accelerated electron beam. This affects the beam's quality and represents an obstacle on a path towards higher intensity and greater reliability. Different techniques are being developed to make modern accelerating cavities selective with respect to the operating mode and suppress HOM wakefields.

The research that is reported here demonstrates suppression of HOMs in a Photonic Band Gap [2] (PBG) room-temperature traveling-wave accelerating structure operating at 11.700 GHz. As shown in Figure 1, PBG structures employed for microwave accelerators represent periodic lattices of metal rods. The periodic lattice is designed to have a photonic band gap [3], which is a range of microwave frequencies that cannot propagate through the structure and get reflected. The presence of a band gap in a 2D crystal of rods allows the confinement of an accelerating (TM_{01}-like) mode in a so-called "PBG waveguide", formed by a defect such as a missing rod, at the center of the PBG structure. The PBG structure is periodically loaded with metal disks with irises which support the rods and slow down the electromagnetic wave for efficient interaction with an electron beam propagating with the speed of light [4–7]. The microwave power is fed through a rectangular waveguide and couples to an accelerating mode in the defect. However, the periodic structure does not confine higher frequency HOMs which may be generated by an electron beam while propagating through the accelerator. HOMs freely radiate towards the periphery of the PBG structure and can be damped by different means in the vacuum chamber which hosts the PBG accelerator. The mode selective properties of the PBG structure provide means for effective HOM suppression as was observed in the experiment described in this paper.

In 2005 the team at Massachusetts Institute of Technology (MIT) conducted the first ever demonstration of acceleration in a PBG accelerator [6, 7]. Two attempts to experimentally demonstrate some suppression of HOMs in PBG accelerating structures were conducted to date [8, 9]. The team at MIT excited the PBG accelerating structure of Ref.[6, 7] with a train of two hundred 1 ps

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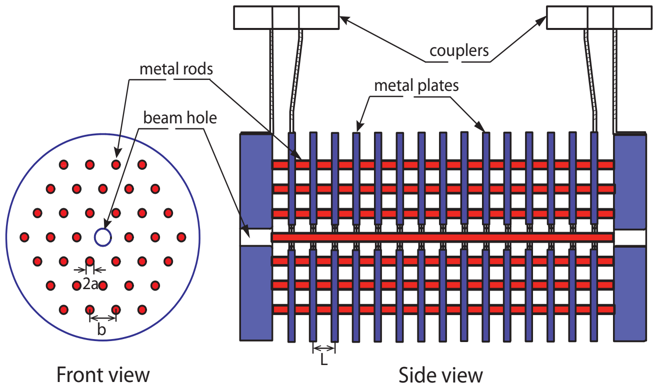

FIG. 1. A conceptual schematic of the Photonic Band Gap accelerator structure.

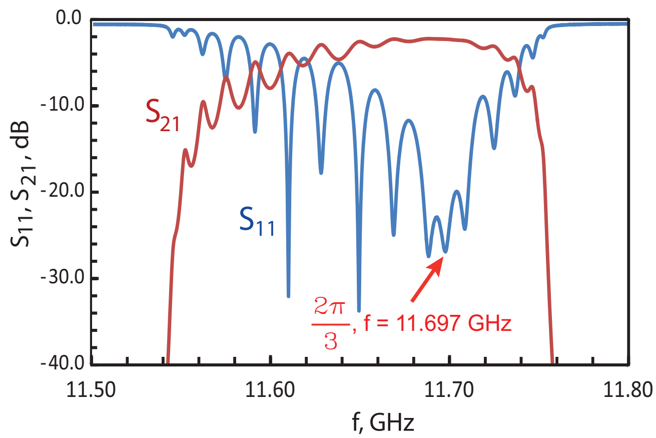

FIG. 2. Transmission (S_{21}) and reflection (S_{11}) in the tuned 16-cell PBG accelerator structure.

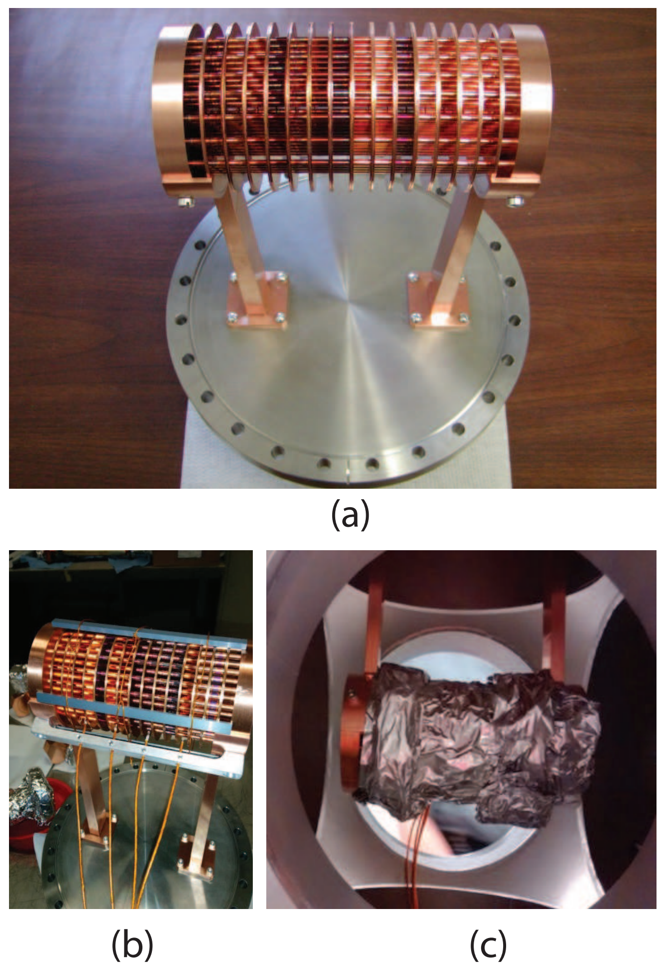

FIG. 3. (a) Photograph of the electroformed 11.700 GHz PBG accelerator structure installed on the 10 inch stainless steel flange. (b) Photograph of the PBG structure with six SiC slabs for attenuating wakefields and pickup loop antennas. (c) Photograph of the PBG structure with no SiC attenuators, wrapped in foil and installed in the vacuum chamber.

long electron bunches periodically spaced at 17.140 GHz with the charge of 1-18 pC per bunch [8]. Radiation was observed at the downstream output port of the structure which contained the frequencies of 17 GHz and 34 GHz and scaled quadratically with current. However, because the electron bunches were spaced periodically at the frequency of the fundamental accelerating mode, observation of significant wakefield radiation into important HOMs such as the dipole mode was impossible with the MIT setup. A different test was conducted at Argonne National Laboratory (ANL) [9]. ANL's team fabricated a three-cell X-band standing wave PBG structure with no power couplers. The wakefields were excited by a single electron bunch with a charge up to 80 nC. Major monopole and dipole modes were identified in the signal collected with probes placed at the periphery of the structure. The gradient was calibrated with a variable delay low charge witness bunch following the high charge drive bunch. However, the ANL structure was a standing wave structure and not a traveling-wave PBG accelerator. This paper reports observation of wakefields and demonstration of HOM suppression in a traveling-wave PBG accelerator structure.

To conduct the wakefields testing, we designed a 16-cell traveling-wave (TW) $2\pi/3$-mode PBG accelerating structure to operate at the frequency of 11.700 GHz. This frequency is equal to 9 times the operational frequency of the Argonne Wakefield Accelerator (AWA) facility at ANL (1.3 GHz) [10], where the wakefield experiment was to be conducted. The accelerator characteristics of the designed structure were similar to those of the 6-cell MIT PBG accelerator [6, 7], which remained the only PBG accelerator structure tested with an electron beam to date. Table I summarizes the design's dimensions and accelerator characteristics.

Similar to the cells of the MIT 17 GHz PBG accelerator [7, 11], the 11.700 GHz PBG cells were electroformed and tuned by etching. However, unlike the short 6-cell MIT PBG accelerator structure, which was fabricated as a single piece, each 11.700 GHz cell was electroformed

TABLE I. The dimensions and accelerator characteristics of the traveling-wave PBG accelerator structure at 11.700 GHz.

Frequency (TM_{01} mode)	11.700 GHz
Phase shift per cell	$2\pi/3$
Spacing between the rods, b, (TW cell/coupler cell)	10.33 mm/10.30 mm
Rod radius, a, (TW cell/coupler cell)	1.55 mm/1.54 mm
a/b	0.150
Length of the cell, L	8.53 mm
Diameter of the iris	6.31 mm = 0.250 in
Thickness of the iris	1.90 mm = 0.075 in
OD of the accelerator cell	76 mm = 3 in
Ohmic Q-factor, Q_w	5000
Shunt impedance, r_s	72.5 MΩ/m
$[r_s/Q]$	14.5 kΩ/m
Group velocity	0.015 c
Gradient	$15.4\sqrt{P\,[\mathrm{MW}]}$ MV/m

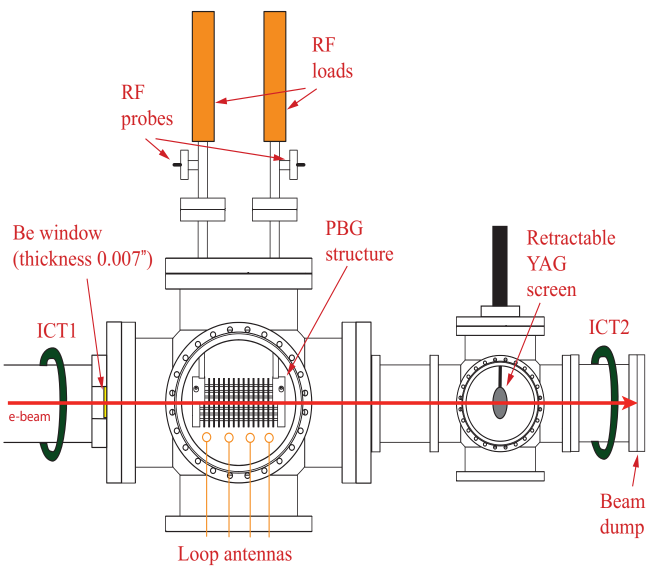

FIG. 4. The experimental setup on the beamline at Argonne Wakefield Accelerator.

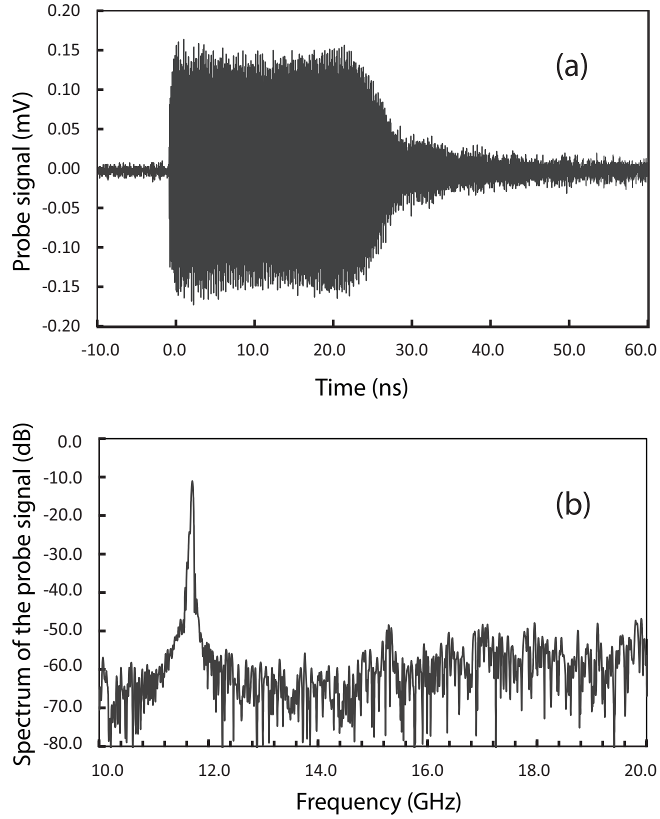

FIG. 5. The rf signal in the downstream coupling waveguide of the PBG structure: (a) time-domain; (b) Fourier transform. The transmitted charge is approximately 0.4 nC.

and tuned separately. Next, the cells were put together in a structure of 2 coupler cells and 14 traveling-wave cells. The clamped structure was cold-tested, and the final cold test results are described in [12]. The coupling curves for the tuned structure are shown in Figure 2 with the dip in the transmission curve at 11.697 GHz (in air) corresponding to the accelerating $2\pi/3$ mode. The electroformed PBG cells could not be brazed due to internal stresses [13]. After numerous discussions, a vacuum-compatible Hyson EA9394 epoxy was identified as means to join the cells together. The chosen epoxy was not conductive, but the proper operation of the accelerating structure required good electrical contact between the neighboring cells. The electrical contact was ensured by fabricating elevated rings around the beam holes and polishing them to a mirror finish. The epoxy did not cover the elevated rings. The structure was pressed together so that the polished rings made good contact with the rings of the neighboring cells. The final bonded structure was cold-tested again to make sure that its coupling curves did not change [14].

Next, the structure was bolted onto a 10-inch stainless steel flange (Figure 3(a)). The flange was installed on a vacuum chamber at the end of the AWA beamline. The schematic of the experiment is shown in Figure 4. The vacuum chamber was isolated from the main beamline by a thin beryllium (Be) window due to a concern that the electroformed structure would not be able to meet the stringent vacuum requirement of 10^{-10} torr dictated by the use of a cesium telluride photocathode in the photoinjector [15]. A single bunch of electrons with the length of approximately 1.1 mm and the energy of 65 MeV was injected through the Be window into the structure. The charge transmitted through the PBG accelerator structure varied between 0.25 nC and 6.3 nC for a single bunch as measured by the integrating charge transformer (ICT) located downstream of the PBG chamber. RF probes were used to record the spectrum of the excited wakefields. The input and the output waveguides of the structure were connected to the directional couplers

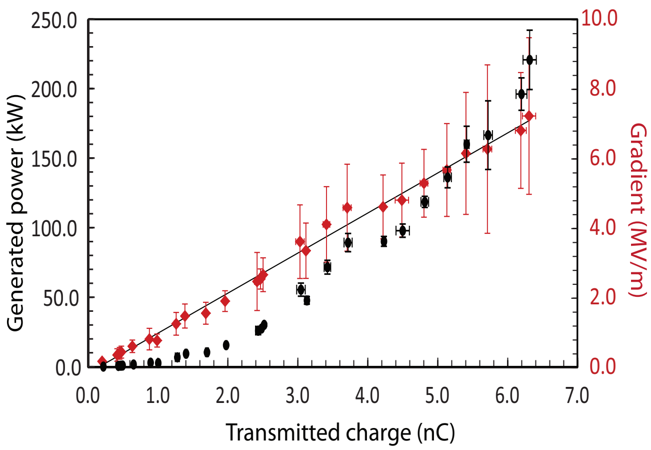

FIG. 6. Measured power in the downstream coupling waveguide of the PBG structure plotted as a function of transmitted charge. Also shown is the gradient in the accelerating structure computed from the measured power.

with probes that sampled the transmitted power. At the periphery of the structure four loop antennas were installed as shown in Figure 3(b) to sample the excited wakefields by coupling to their magnetic field.

First we studied the rf signal in the downstream coupling waveguide. Figure 5(a) shows the rf pulse measured in the downstream waveguide. The pulse was generated by an electron bunch with the charge of approximately 0.4 nC. The length of the pulse is close to 30 ns, in very good agreement with simulations. The signal was Fourier transformed to study the spectrum (Figure 5(b)). It was found that the spectrum was dominated by the fundamental mode at 11.700 GHz with very little power transmitted at any other frequencies. Next, the charge of the electron bunch was varied, and the dependence of the generated power on the transmitted charge was recorded (Figure 6). The power scaled quadratically with the transmitted charge as predicted. The rf signal in the upstream coupling waveguide was also studied and contained various noise.

Next we analyzed the rf signal picked up by the loop antennas at the side of the structure. To obtain clear signal from the loop antennas we had to combat a strong noise caused by the electrons that were scattered by the Be window [15] and hit the PBG structure and the vacuum chamber. The number of scattered electrons varied between 50 and 70 per cent, as measured by the two ICTs placed before and after the PBG chamber; more electrons were scattered for the higher bunch charge. The previous study of the electron beam scattering from the Be window (with no PBG structure) [15] indicated that the transverse rms size of the electron bunch after passing through the window could be up to a few millimeters. From this measurement we concluded that a good fraction of electrons was most likely hitting the front of the PBG structure, could not enter the structure's beam aperture, and was scattered in the vacuum chamber causing noise. A few adjustments to the experimental configuration were required. One particular adjustment was that the loop antennas were placed very close to the PBG structure (Figure 3(b)) to increase the signal-to-noise ratio. The clearest signal and the least noise came from the most downsteam antenna. The antenna's signal contained the fundamental mode (leaking at a low level through the PBG structure) and a number of low-Q-factor HOMs with frequencies in between 15 GHz and 20 GHz. We recorded the antenna's signal in two different configurations with the least noise: in an open PBG structure with 6 SiC absorbers attached to the sides of the structure (Figure 3(b)), and in a PBG structure wrapped in foil with SiC absorbers removed (Figure 3(c)). The structure with SiC absorbers had strongly attenuated HOMs, only slightly above the noise level (Figure 7(a)). However, for the same transmitted charge, the structure wrapped in foil with SiC absorbers removed, had much more pronounced HOMs, which could not radiate out through the foil (Figure 7(b)) and were confined. These measurements demonstrated the effectiveness of the PBG structure to filter HOMs.

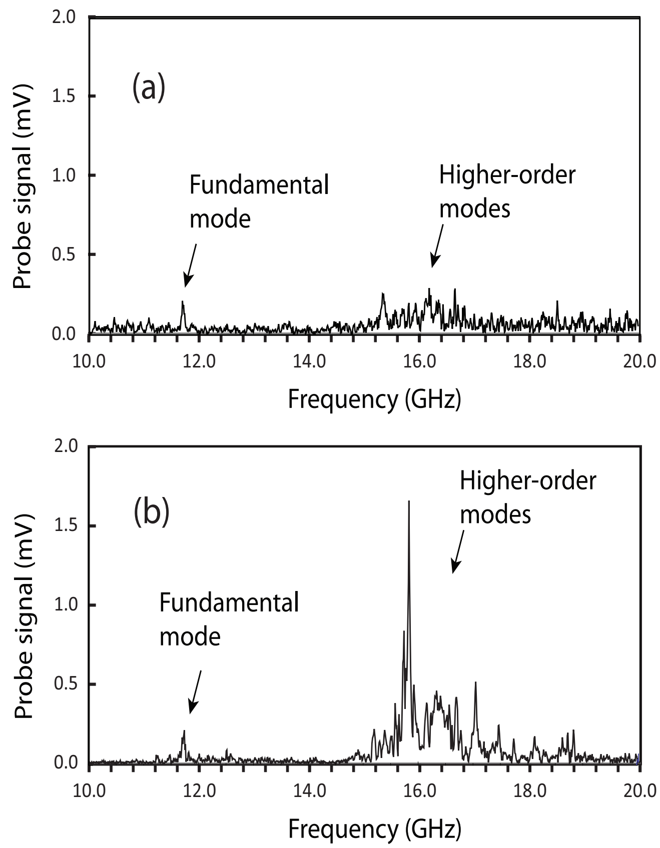

FIG. 7. The rf spectrum of the signal picked up by a loop antenna at the periphery of the PBG structure: (a) the structure with six SiC absorber slabs; (b) the structure wrapped in foil. The transmitted charge is approximately 3 nC.

This work represents the first experimental demonstration of suppression of higher order mode wakefields in a room-temperature traveling-wave photonic band gap accelerating structure operating with an electron beam. An X-band 16-cell TW PBG accelerator structure was designed, fabricated, tuned, and tested with a high charge beam at the Argonne Wakefield Accelerator. The spectrum of wakefields excited by a single electron bunch passing through the PBG accelerator was recorded. The wakefields were measured in two different configurations: in the open PBG structure with 6 SiC slabs installed at the periphery and in the PBG structure wrapped in foil. It was demonstrated that the level of wakefields was much lower for the open structure with absorbers than for the structure wrapped in foil that confined wakefields. The experiment confirms the long-standing prediction that the PBG structure filters out higher order modes and is effective for the long-range wakefields suppression.

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