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Modeling, Simulation and Optimization of Piezoelectric Bimorph Transducer for Broadband Vibration Energy Harvesting in Multi-Beam and Trapezoidal Approach

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Abstract

The objective of the research is to design a broadband energy harvester device through the multi-beam approach and non-linear trapezoidal geometry approach. The performance of the composite piezoelectric PZT-PZN polycrystalline ceramic material is simulated using COMSOL Multiphysics, and results are compared using series configuration of a composite bimorph energy harvester which vibrates at its 1st fundamental frequency. We chose a five cantilever multibeam harvester to demonstrate that individual fundamental modes of the beams can achieve a broader frequency band and generate power. Authors also show that composite trapezoidal beam design leads to high power density broadband frequency response. The multibeam approach resulted in broader bandwidth of 18 Hz while generating a power density of 0.0913 mW/cm^3 whereas the trapezoidal shape generated 2.3 – 2.5 mW/cm^3 with a bandwidth of 4 to 6 Hz. Authors believe that these results could help design broadband energy harvesters to enhance power density as well as bandwidth.

Keywords: multi-beam, non-linear trapezoidal, polycrystalline, bimorph, broadband

As the demands of alternative energy source emerges from health care monitoring and remote sensing applications, broadband piezoelectric energy harvesters have recently attracted extensive attentions as the broadband design overcomes the narrow frequency response. The current portable electronics (e.g. sensors, actuators) solely relied on battery source. The battery technology becomes the limit of low-power portable electronics, as periodic battery replacement limits the applications of these devices. Researchers have studied broadband piezoelectric energy harvesters: numerous piezoelectric broadband designs have been proposed in literatures (Priya & Inman, 2008). Liu et al. (2008) studied a micro array of a multi-layered composite cantilever beam generating 3.98μw of effective electric power, however, the frequency range for operation was not explained in details. As it is widely known that single traditional piezoelectric cantilever beam has one major drawback: narrow frequency response (Hosseini & Hamedi, 2015). Electric performance of the cantilever vanishes significantly when vibration frequency deviates from resonance frequency of the cantilever beam. The letter addresses this problem with multi-beam design and trapezoidal beam design to effectively increase the frequency band responses of piezoelectric energy harvester. Salmani, Rahimi, and Hosseini Kordkheili, 2015 had studied the exponential tapered as well as the trapezoidal piezoelectric harvester, yet the research only studied one piezoelectric plate. Many researchers reported that trapezoidal and tapered beam design that lead to better performance of the energy harvester. Ramalingam Usharani. et al. (2016) reported that the maximum voltage is available when the taper angle is at 2.25 degrees. Rouhollah and Mohsen studied the "trapezoidal v-shaped" beam and proposed an analytical formula for 1st resonance frequency for the rectangular beam and tapped beam: the authors showed that the analytical 1st resonance frequency of the tapped beam is twice as much as that of rectangular beam (Hosseini & Hamedi, 2016). Yet the authors did not discuss performance metrics such as electrical energy performance or operational bandwidth of the v-shaped beam or trapezoidal beam (Hosseini & Hamedi, 2016). Benasciutti et al. studied "trapezoidal" and "reversed trapezoidal" bimorph cantilever beam, the author showed that the power density of "reversed trapezoidal" beam is consistently higher than that of "trapezoidal" (Benasciutti, Moro, Zelenika, & Brusa, 2010), which agrees with our result of maximum power density for the 1st trapezoidal beam design and the 2nd trapezoidal beam design in this work, yet the piezo material used in two researches are different: Benasciutti et al. did not include bandwidth result and used PSI-5A4E PZT material (Benasciutti, Moro, Zelenika, & Brusa, 2010), while PZTPZN-Scheme4 material is used in this work (Bedekar, Oliver, & Priya, 2010).

Researchers paid attention to the multi-beam approach as different beam has different natural vibrating frequency. The intention was to combine multiple cantilevers into one system, so that the system can response to a spectrum of vibrating frequencies: T M. Ferrari. et al studied a multi-beam system that they found that voltage bandwidth was increased (Cerini et al., 2014); Jens Twiefel. et al. also mentioned that the linear mismatched array can improve bandwidth responses (Twiefel, Neubauer, & Wallaschek, 2013). The multi-beam approach is proposed to achieve a broader band frequency response for harvesting ambient, low frequency energy. The research group varied the lengths from 40mm to 60mm (4mm interval), widths from 2mm to 18mm (4 internal) and thicknesses from 0.25mm to 0.35mm (0.05mm interval) of 5 piezoelectric beams and connected them in series. Badran. et al. claimed that the optimal distance between each cantilever in the multi-beam system plays an important role in boosting energy harvesting, and achieved 30 times to 1800 times stored energy (Badran & Ghali, 2012). Sunithamani et al. reported that piezoelectric energy harvester reached maximum stored electrical energy when the cantilever beam reaches “optimal piezoelectric layer thickness” (Sunithamani, Lakshmi, & Flora, 2012). Chen, Yang, and Deng (2009) compared the analytical stain of rectangular, trapezoidal and triangular composite piezoelectric beams and suggested the strain decreases slower as the length of the triangular beam grows than that of rectangular and trapezoidal beam, the authors showed that strain , stress and open circuit voltage is higher triangular design in ANSYS10 Finite element simulation , yet no loading optimal resistor is connected in a circuit nor bandwidth of power density results are not reported, as the result of open circuit voltage alone is not predicative enough for the beam’s performance.

A PZT-PZN polycrystalline ceramic Scheme4 composition samples were analyzed: 0.8 $[Pb(Zr_{0.52}\ Ti_{0.48})O_3]$ – $0.2[Pb(Zn_{1/3}\ Nb_{2/3})O_3]$ in all models during this research. Scheme4 was chosen because it has the large power density (0.2676 mW/cm^3 predicted and 0.1713 mW/cm^3 measured (Bedekar, Oliver, & Priya, 2010)) as it was pointed out by Bedekar et al. SEM images of the Scheme4 material are shown in Figure 1 and the material properties values are shown in Table II ((Bedekar, Oliver, & Priya, 2010)). Previously, Chen and Bedekar showed step by step procedures to convert piezoelectric material properties to COMSOL simulation model (Bedekar, Oliver, & Priya, 2010).

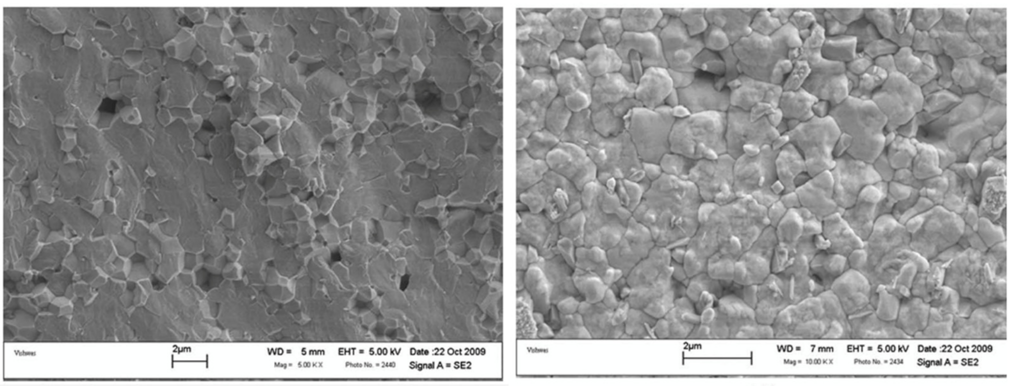

Figure 1. Scheme 4 material - SEM sintered image: WD at 5mm (left) , 7mm (right) [8] (reprinted with permission from IEEE-UFFC)

The strategy to find the maximum electric real power output is: find the 1st resonance frequency (68.303Hz) of the beam, once the 1st resonance frequency of the beam is known, the external resistance was varied from 0.01MΩ to 0.03MΩ with 0.001MΩ resolution; optimal resistance is found at 0.025 MΩ.

Table I. Length, width, thickness, resonance frequency of the linear elastic composite five-beam system with same composite base and no tip mass

Length	Width	Thickness $2T_p+T_s$	Resonance f_r
44mm	10mm	0.55mm	126.86Hz
48mm	10mm	0.55mm	107.67Hz
52mm	10mm	0.55mm	91.79Hz
56mm	10mm	0.55mm	78.33Hz
60mm	10mm	0.55mm	68.303Hz

The average resonance frequency of Five-beam in Table I is 94.57 Hz, and the broadband voltage response is observed in Figure 3.The distance between each pair of beams is kept at 10 mm. T_p is the thickness of one PZN-PZT layer, T_s is the thickness of the UNS C22000 Brass layer, $2T_p+T_s$ is the total thickness of the composite bimorph beam as shown in Figure 7.

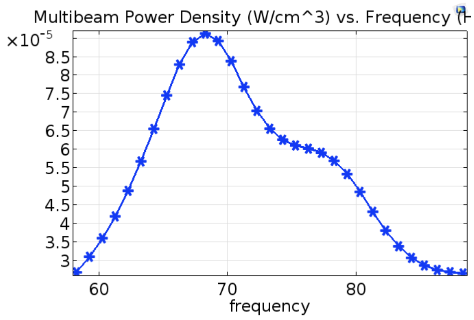

Figure 2. Multi-beam FWHM power density (Watt/cm^3) bandwidth vs. vibration frequency (Hz)

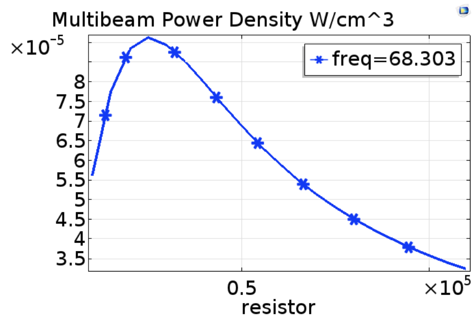

Figure 3. Multi-beam's Power Density in a range of resistive load from 0.01 MΩ to 0.11 MΩ with the resolution of 0.005 MΩ under 1st resonance frequency at 68.303Hz, the peak power density is at 0.0913mW/cm^3

With the optimal resistance found at 0.025 MΩ under 1st resonance frequency (68.303Hz), the power density-frequency response study was performed from 58.303Hz to 78.303Hz with 1Hz interval and can be seen in Figure 3 with the optimal 0.025 MΩ resistor loaded in the circuit. When the system is vibrating at 68.303Hz, the maximum Von Mises stress is shown at the fixed end of the longest 60mm beam in Figure 4. The results were consistent with the 1st resonance frequency shown in Table I. The volume of the five-beam system is 1.3 cm^3.The real power density of the five-beam reaches a maximum of 0.0913 mW/cm^3 (0.119 mW) when vibrating in 68.303Hz with the optimal resistor 0.025 MΩ connected in the series configuration. Full width half maximum bandwidth (FWHM) of the real power density is found by scanning the vibration frequency around the 1st resonance frequency of the five-beam system: the scan ranges from 58.303Hz to 88.303Hz with 1Hz interval, the system reaches the (minimum) half real power density 0.0456 mW/cm^3 when vibrating 62.303 Hz and 80.303 Hz, reaches peak real power density 0.0913mW/cm^3 at the 1st resonance frequency at 68.303Hz ; therefore the FWHM real power density bandwidth of the five-beam system is 18Hz (62.303Hz-80.303Hz).

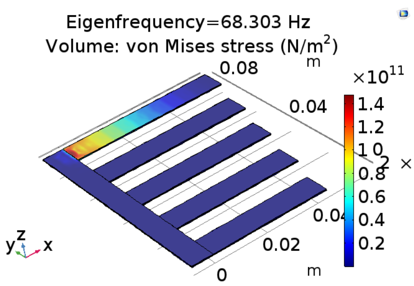

Figure 4. Von Mises stress of a five-beam system connected by a common beam using same PZT-PZN Scheme4 composite material and vibrating at 1st resonance frequency at 68.3Hz in 238078 elements (degrees of freedom) in extreme fine mesh of 1.3 cm^3, with the 0g tip mass boundary condition on the edge of all free end of five-beam system, the dimension of the base is 8mm x 90mm x 0.55mm

Although the FWHM bandwidth of the five-beam system is beginning to show its promising results to the designing of the broadband energy harvesters, the trapezoidal beam design (non-linear shape) is another approach to enhance energy harvester's frequency bandwidth performance. The research group started with two trapezoidal beams which are shown in Figure 5.

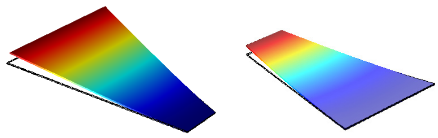

Figure 5. Displacement of two different trapezoidal piezoelectric bimorph beam designs vibrates at the 1st resonance frequency, the left subplot is 1st design, right subplot is 2nd design, the shorter width is at 20mm, the longer width is at 60mm, both designs have 0 g tip mass boundary condition on the edge of the free end (warm color area), the other end is fixed on the blue colored area

The shorter width W_1 ranges from 4mm to 20mm (4mm interval), and longer width W_2 ranges from 40mm to 60mm (4mm interval). The length L of each trapezoidal plate is 60mm, and thickness of the single plate is 0.25mm, Brass layer thickness is 0.05mm, therefore the total composite thickness of the bimorph is 0.55mm for bimorph, as the side views are shown in Figure 6 and cross section view of the composite beam is shown in Figure 7.

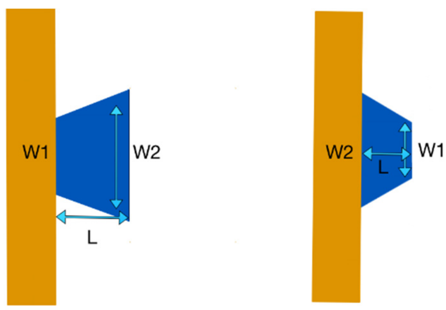

Figure 6. Top-down view of the bimorph piezoelectric trapezoidal beam, the left subplot is the 1st design and right subplot is the 2nd design, W_1 is shorter width, W_2 is the longer width

Figure 7.Thickness view of the composite multi-beam and trapezoidal beam's upper and lower PZTPZN Scheme4 layer thickness: 0.25mm, middle layer (UNS C22000 brass) thickness: 0.05mm

In both subplots of Figure 6, the orange rectangle shows the fixed support end. The x-axis increase shows W_1 increases in each periodic section and W_2 increases in Figure 8, Figure 9, Figure 10, Figure 11, Figure 12 and Figure 13

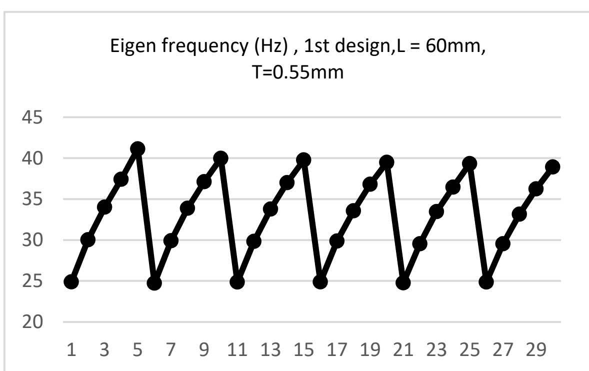

Figure 8. Resonance frequency vs 30 permutation of 1st trapezoidal piezoelectric composite bimorph beam design

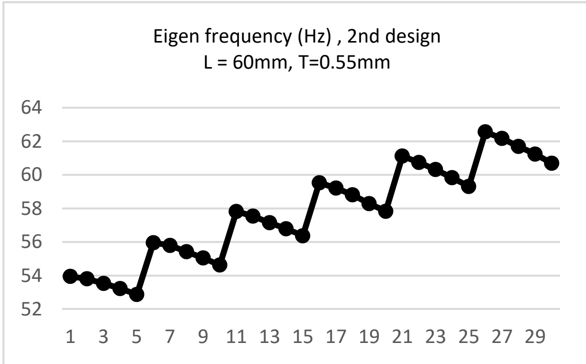

Figure 9. Resonance frequency vs 30 permutation of 2nd trapezoidal piezoelectric composite bimorph beam design

The 1st resonance frequency increases as the shorter widths of the beam increases as pattern is shown in Figure 8 and Figure 9: among 30 trapezoidal permutations of geometries for each trapezoidal piezoelectric composite bimorph beam design, the average resonance frequency of 1st trapezoidal beam design is 33Hz, the average resonance frequency of 2nd trapezoidal beam design is 58Hz. It indicates that the 1st trapezoidal beam design is suitable in harvesting lower vibration frequency applications, while the 2nd trapezoidal beam design is suitable in harvesting higher vibration frequency applications. The size of mesh is set to “extreme fine” to increase the accuracy of Eigen frequency. The element size does have a minor effect on numerical precisions of all simulation results.

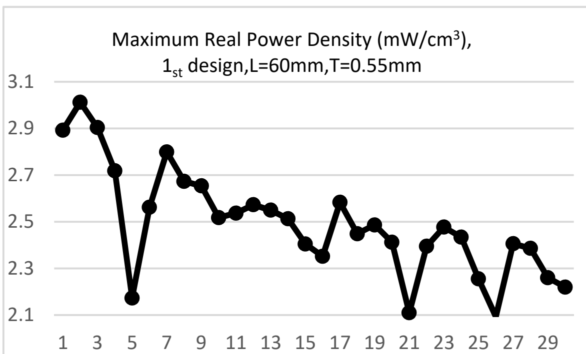

Figure 10.Maximum electrical power density vs 30 various geometries of the 1st trapezoidal composite piezoelectric bimorph beam in closed circuit with corresponding optimal resistor load

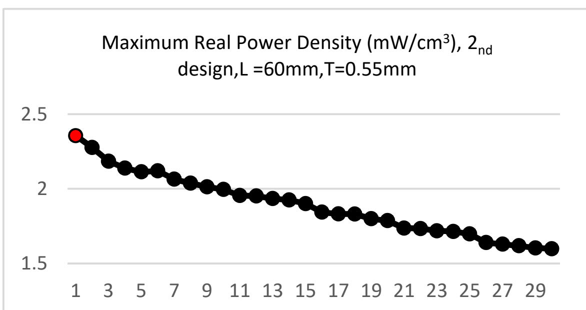

Figure 11. Maximum electrical power density vs 30 various geometries of the 2nd trapezoidal composite piezoelectric bimorph beam in closed circuit with corresponding optimal resistor load

The maximum electric real power density is defined by the unit real power consumed by the corresponding optimal resistor connected in the closed circuit. Both trapezoidal designs share similar pattern as shown in Figure 10 and Figure 11: the electric power (y-axis) decreases as W_1 and W_2 of beam increases (x-axis). The length of each trapezoidal beam is fixed at 60mm, and the thickness of the beam is fixed 0.55mm. The maximum electrical real power density reaches 3.01mW/cm^3 (volume is 0.72cm^3 and generated power is 2.167mW) for the 1st trapezoidal composite beam design when W_1 reaches 8mm, and W_2 reaches 40mm with the optimal resistor load 0.06MΩ ; The maximum electric real power density reaches 2.36mW/cm^3 (volume is 0.66cm^3 and generated power is 1.558mW) for the 2nd trapezoidal composite beam design when W_1 reaches 4mm, and W_2 reaches 40mm with the optimal resistor load 0.06MΩ as shown in Figure 10 and Figure 11. The reason the largest maximum electric real power density appears at the beginning of the geometry permutation plots for both trapezoidal composite piezoelectric bimorph beam design is: the maximum electric real power density is more sensitive to the volume of the beam than any other factors. The optimal resistance scan ranges from 0.01 MΩ to 0.5 MΩ with interval of 0.025 MΩ for all 30 permutations of both trapezoidal piezoelectric bimorph beam designs. The maximum electric real power density is compared between both trapezoidal piezoelectric bimorph beam designs due to the fairness of performance comparison when taking the size (volume) of the energy harvester out of the equation.

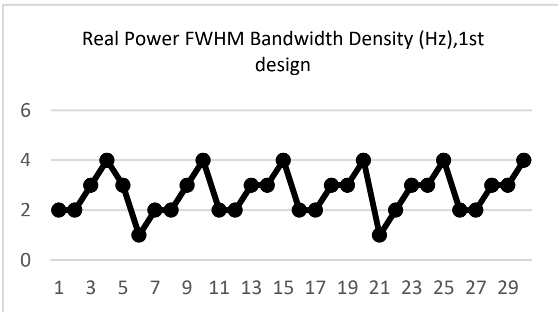

Figure 12. Real electrical power density FWHM bandwidth vs 30 various geometries of the 1st trapezoidal composite piezoelectric bimorph beam design in closed circuit with corresponding optimal resistor load fixed

To better describe the bandwidth performance of the trapezoidal beam, the Full Width Half Maximum (FWHM) bandwidth of real electrical power is evaluated on both trapezoidal beam designs: the length L is fixed at 60mm, the composite thickness T is fixed at 0.55mm, and the Full Width Half Maximum (FWHM) bandwidth of real electrical power is determined by scanning +/- 5Hz (1Hz interval) around the 1st resonance frequency with optimal resistance fixed in each corresponding widths (W_1,W_2) geometry permutation of the trapezoidal beam as shown in Figure 12 and Figure 13.

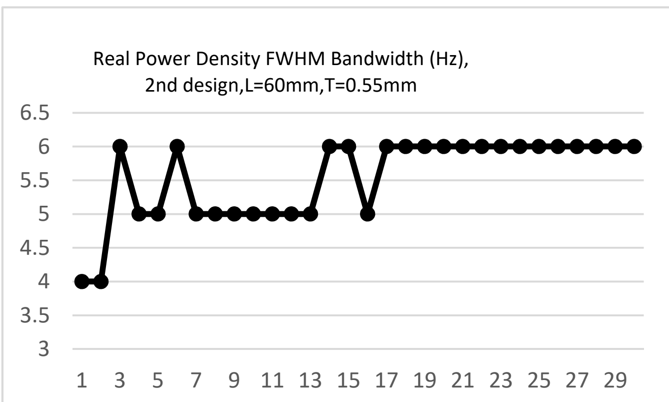

Figure 13. Real electrical power density FWHM bandwidth vs 30 various geometries of the 2nd trapezoidal composite piezoelectric bimorph beam design in closed circuit with corresponding optimal resistor load fixed

For the 1st trapezoidal design, the average of real power density FWHM bandwidth of 30 geometry permutations is 2.7Hz, the maximum is 4Hz (min. power density 1.066 mW/cm^3, maximum power density 2.517 mW/cm^3, W1=20mm,W2=44mm, Volume = 0.96cm^3, Power = 2.42mW) and the minimum is 1Hz (min. power density 0.966 mW/cm^3, maximum power density 1.898 mW/cm^3) as shown in Figure 12.

For the 2nd trapezoidal design, the average of real power density FWHM 30 geometry permutations is 5.3Hz, the maximum is 6Hz (min. power density 0.799mW/cm^3, max. power density 2.0415mW/cm^3 W_1=12 mm, W_2=40 mm, Volume = 0.78cm^3, Power = 2.42mW) and the minimum is 4Hz (min. power density 1.139mW/cm^3, max. power density 2.356mW/cm^3) as shown in Figure 13. The 2nd beam design's real power density FWHM bandwidth is less sensitive to the discrete geometry increments than the other designs, which contribute to the shape of Figure 13.

The key metrics comparison of the multi-beam design and the trapezoidal designs is tabulated in the Table III : Multi-beam design has the best real power density (18Hz) FWHM bandwidth performance, while the 1st trapezoidal beam design has the best minimum power density (1.066 mW/cm^3) as well as maximum power density (2.517 mW/cm^3).

In conclusion, the multibeam piezoelectric harvester generated 0.0913 mW/cm^3 of power and offers wider bandwidth (18 Hz) than the trapezoidal beam designs (4-6 Hz), yet the trapezoidal beam designs have superior power density performance of 2.3 – 2.5 mW/cm^3. The simulation results tabulated in Table III show that the multibeam approach and the trapezoidal piezoelectric beam approach are two of the promising approaches in designing the high-power density, broadband piezoelectric energy harvesters.

Table II. Material Value property name and value [8]

Value		*Name*
k_{31}	0.32	Electro-Mach coupling factor
d_{31}	153.73	Piezoelectric charge constant: pC/N
g_{31}	0.011	Piezoelectric voltage constant: Vm/N
k_p	0.59	Coupling coefficient
ε_r	1588	dielectric constant
Q_m	78.7	mechanical quality factor
ρ	7879	density (kg/m^3)
ζ	0.025	mechanical damping ratio
temp	1100	sintering temperature (°C)
T	3	sintering time (hour)
Mt	2.36	tip mass (g)
d_{33}	400	Piezoelectric charge constant: pC/N
g_{33}	0.028	Piezoelectric voltage constant: Vm/N

Table III. FWHM bandwidth, Min/Max real power density of beam

Design	Max. FWHM Bandwidth	*Min. Power Density*	*Max. Power Density*
multi-beam	**18Hz**	0.0456 mW/cm^3	0.0913 mW/cm^3
1st trapezoidal	4Hz	**1.066 mW/cm^3**	**2.517 mW/cm^3**
2nd trapezoidal	6Hz	0.799 mW/cm^3	2.356 mW/cm^3

Results of both trapezoidal power density in Table III are higher than that of a rectangular shaped composite beam (0.2676 mW/cm^3 predicted and 0.1713 mW/cm^3) measured and reported by Bedekar et al. [8] Yet the maximum power results in Table III is slightly lower than that of Benasciutti et al. reported trapezoidal shaped beam (3.9 mW/cm^3).

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