A Wideband Magnetic Frequency Up-converter Energy Harvester

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Abstract

Many sensor applications require small and non-invasive methods of powering, such as marine animal tracking and implantable healthcare monitoring. In such cases, energy harvesting can be a viable solution. Vibrational energy harvesting is abundantly available in the environment. These vibrations usually are low in frequency and amplitude. Conventional vibrational harvesters convert the environmental vibrations into electrical signals; however, they suffer from low voltage outputs and narrow bandwidths, limiting the harvesting to a small range of frequencies. In this work, a new mechanical harvester is introduced using a magnetic frequency up-converter. It is implemented using attractive-force magnetic coupling between a soft magnet and a permanent magnet to convert low-frequency vibrations into high-frequency pulses. Combined with a piezoelectric generator, the harvester generates a high output voltage for an extended bandwidth of operation. The proposed harvester shows a 50.15% increase in output voltage at the resonant frequency (12.2 Hz), resulting in 14.79 V at 1.0 g, with a maximum peak voltage of 16.28 V. The bandwidth of operation ranges from 10.77 Hz to 22.16 Hz (11.39 Hz), which compared to a single-beam harvester shows an increase of 3250% of the bandwidth, where the average power is greater for 92.56% of this bandwidth.
Introduction

There has been increasing demand for the development of low-cost, low-power sensors for applications like artificial intelligence (AI), the internet-of-things (IoT), and 5G technology, with an estimated market of wireless sensor networks (WSN) to exceed $94 billion by 2025\textsuperscript{[1]}. These wireless sensors are essential in applications such as earthquake monitoring systems, seismic detection in tunnels, and structural health monitoring\textsuperscript{[2]}. Harvesting energy from the environment allows for compact, lightweight, and battery-less devices that can operate in inaccessible or remote areas. Mechanical vibrations can produce 330uW/cm\textsuperscript{2}, which is enough to power low-power sensors\textsuperscript{[3]}. Furthermore, these vibrations are available at night, in remote places, underwater and underground, and are only limited by the vibrations themselves\textsuperscript{[4]}. They can be blast-induced ground vibrations, which are commonly found in civil construction and mining\textsuperscript{[5]}. Natural vibrations can also be seen in seismic waves caused by earthquakes and volcanoes, in both land and water. These natural vibrations have frequencies ranging from 0.1 to 20 Hz\textsuperscript{[6]}. Vibrations can also be found in transportation systems, where vehicles induce frequencies in the range of 1-2Hz and 12Hz\textsuperscript{[7]} and railways vibrate at around 15-30Hz\textsuperscript{[8]}

A typical vibrational harvester system consists of a mechanical structure, like a beam, a transducer, a rectifier, and a storage element to store the harvested energy. This can be seen in Figure 1(a). The beam gets excited into oscillating through the ambient environment vibrations. It can be tuned to resonate at a specific frequency by tuning the beam's properties and dimensions. Nevertheless, this resonant frequency typically has a narrow bandwidth, limiting the frequency range in which the beam can oscillate efficiently, as shown in Figure 1(b). The transducer (i.e., piezoelectric material) is responsible for converting the mechanical stress caused by the beam's motion into electrical energy\textsuperscript{[9, 10, 11-13]} Note that the output voltage of the transducer is maximized by offsetting it from the neutral plane and by placing it at the maximum stress position (i.e., on top and near the fixed end of the beam), as shown in Figure 1(c).\textsuperscript{[14]} The rectifier block (e.g., diodes) converts the transducer's AC signal into a DC voltage. In order for
the rectifier to operate, the voltage across the rectifier (i.e., the generated voltage by the transducer) should be greater than the threshold voltage of the rectifier (typically ranges from 0.35V to 1V). This becomes an issue, especially when harvesting environmental vibrations, which typically produce lower voltage than higher frequency vibrations. Even when the produced AC voltage is greater than the threshold voltage, a percentage of the harvested energy (equivalent to the threshold voltage) is lost across the rectifier, thus reducing the system's overall conversion efficiency. In other words, improving the system's overall performance can be achieved by amplifying the output voltage of the harvester before passing it to the rectifier.

The idea of enhancing the bandwidth and amplifying the voltage before rectification to minimize the rectification loss has been discussed by many (Supplementary Information 1). Gu and Livermore tackled the idea by having a Low-Frequency (LF) beam colliding with a High-Frequency (HF) piezoelectric generator at high force, thus increasing the output voltage. This device, however, is susceptible to elasticity damage, and the performance can degrade over time. Jung and Yun produced a frequency up-converter by integrating beams with buckled bridges. Although the idea of contactless frequency up-conversion avoids the issue of durability, the design requires high acceleration conditions to excite the device. Luo et al. investigated the use of multiple beams to enhance the bandwidth of their system. However, the device requires five beams with masses on their tips, making the harvester heavy and bulky. Voltage amplification through magnetic coupling has been implemented by many, as it amplifies the force applied to the system without affecting its durability. An underwater harvester presented by Zou et al. uses magnetic coupling between a beam and a flextentional piezoelectric transducer to amplify the output. Zhao et al. produced a wind energy harvester using magnets to minimize torque resistance while also amplifying the output. They also used magnetic coupling to create a harvester for irregular low-frequency vibrations. Another design by Lin et al. uses magnets to increase the bandwidth and power achieved from vibrations. These magnetically coupled devices utilize
the repulsion force of magnets to achieve a bistable system with greater power. However, for the system to translate from one stable-state to another, a potential barrier needs to be overcome, which is difficult to achieve under low acceleration conditions.\cite{12}

This work introduces a vibrational harvester with an integrated contactless magnetic frequency up-converter mechanism. It utilizes attractive-force magnetic coupling between a soft magnet and a permanent magnet, allowing the system to operate at low-frequencies and low acceleration conditions. It offers high output voltage for extended bandwidth, which is essential for harvesting ambient vibrations.

**Concept**

The contactless magnetic frequency up-converter harvester is depicted in Figure 2(a). It consists of an LF beam, a permanent magnet attached to the LF beam tip, an HF beam made of a soft magnetic material, and a piezoelectric material attached to the fixed end of the HF beam. Note that the LF beam is designed to have a low resonant frequency to capture the environment's LF vibrations efficiently. On the other hand, the HF beam is designed to have a high resonant frequency to generate a higher voltage by the piezoelectric material, as the voltage is proportional to frequency. Using a soft magnetic material aids in achieving a high resonant frequency as it eliminates the need to add a permanent magnet, which would have increased the mass of the HF beam and lowered its resonant frequency. The stray field of the permanent magnet magnetizes the soft magnetic HF beam (more details on the properties of the soft magnet can be found in Supplementary Information 2), thus resulting in attraction force between the HF beam and the poles of the magnet. Once the LF beam and the permanent magnet oscillate due to the environmental vibrations, the magnetic force triggers the HF beam's oscillation and the attached piezoelectric transducer. Note that the polarity of the generated voltage is based on the polarity of the piezoelectric transducer's displacement. Hence, every
time the HF beam bends upwards/downwards, an AC voltage is produced at the output, as shown in Figure 2(b).

Theory

The amplitude of the AC voltage is determined by the displacement and acceleration of the HF beam and the dimensions of the piezoelectric transducer. As the HF beam bends, both tensile and compressive stresses are created across the beam. This bending stress is related to the beam's displacement; the farther the HF beam moves away from its natural position, the greater the stress. The bending stress at the fixed end of the beam is calculated by:

\[ \sigma = \frac{Mc}{I} \]  
\[ M = FL \]  
\[ I = \frac{wt^3}{12} \]

where \( \sigma \) is the bending stress of the beam, \( M \) is the bending moment, which can be represented by the force \( (F) \) acting on the tip of the beam multiplied by the length \( (L) \) of the beam, \( I \) is the moment of inertia, \( c \) is the distance of the stress point from the neutral axis, and \( w \) and \( t \) are the width and thickness of the beam, respectively.\(^{[21]}\) The deflection can be represented by:

\[ \delta = \frac{FL^3(1 - v^2)}{3EI} \]

where \( \delta \) is the deflection of the beam, \( v \) is Poisson’s ratio, and \( E \) is the Young’s modulus of the beam’s material.\(^{[22]}\) Substituting equations (2) and (4) into (1), we get a relationship between the deflection of the beam and the bending stress:
\[
\sigma = \frac{3Ec}{L^2(1 - v^2)} \delta
\]  

(5)

Once stress is applied to the piezoelectric transducer, a charge, \( q \), is generated across the transducer. This charge is determined by:

\[
q = d_{33}A\sigma
\]

(6)

where \( d_{33} \) is the piezoelectric constant along the beam's longitudinal axis, and \( A \) is the cross-sectional area of the piezoelectric transducer.[23] The generated current (\( i \)) by the transducer is related to the change in charge; and hence to the change in displacement of the beam:

\[
i = \frac{dq}{dt}
\]

(7)

\[
i \propto \frac{d\delta}{dt}
\]

(8)

From equation (8), we can see that increasing the current (i.e., power) generated by the vibrational energy harvester is achieved by increasing the speed or the displacement of the HF beam. In our case, both the speed and the displacement are boosted by the forces of the magnets attached to the LF beam. In other words, the LF beam is designed to maximize the magnets' displacement and capture the low-frequency motions produced by the environment (i.e., by having a long membrane made of polymer). The magnets' stray fields pull the HF beam to large distances at a higher speed. This higher speed is achieved when the LF beam can no longer pull the HF beam, and the HF beam is released to vibrate at its natural frequency.

Figure 2(c and d) illustrates a full-motion cycle of the LF beam and the corresponding displacement and output voltage of the HF beam, pulled to a larger displacement due to the magnets. As the LF beam starts to oscillate upwards, it attracts the HF beam with it. This results in a large displacement in the HF beam, giving a positive voltage output (Figure 2(c) subfigure 1). As the LF beam moves further up, the HF beam's elastic force becomes greater than the
magnetic force, so the HF beam is released, creating a large negative spike followed by an oscillation at its natural frequency (subfigure 2). Once the LF beam begins to go down, it again reattracts the HF beam, generating a positive voltage smaller than the previous negative spike (subfigure 3). The HF beam is then pulled downward, creating a negative voltage (subfigure 4). As the LF beam gets further down, it is released from the HF beam, creating a positive spike followed by an oscillation of the HF beam at its natural frequency (subfigure 5). The LF beam then moves upward and reattracts the HF beam, creating a small negative voltage spike (subfigure 6).

The bandwidth of the magnetic frequency up-converter harvester depends on several factors, such as the quality factor, the stiffness, and the mass of both beams. Note that the magnetic forces between the LF and the HF beams act as a nonlinear spring. This magnetic interaction continuously changes the system’s stiffness, thus increasing the bandwidth around the natural frequency.[24] Ibrahim et al. investigated the relationship between the magnetic forces and beam dynamics and modeled such systems' behavior.[24] The magnetic forces between the two beams consist of two components: the longitudinal force that balances the system's stiffness and the transverse force that impacts the deflections of the beams. The gap between both beams changes the strength of these magnetic forces. When the magnetic forces are weak, the system is monostable, and it becomes bistable when the forces are high. When the gap is around the threshold distance, where the system converges to its natural frequency, the beam exhibits a nonlinear behavior at which the system’s bandwidth increases significantly. Figure 3(a) shows the fabricated contactless magnetic frequency up-converter. Figure 3 (b) shows the bistable states of the beams when the system is at equilibrium (i.e., no vibrations), highlighting the attraction of the HF beam to the poles of the permanent magnet.
Measurement Results and Discussion

To measure the energy harvester's performance, it is mounted on a 3D printed stage, acting as the bulk of the harvester. This stage is then fixed onto an electromagnetic shaker (Tira GmbH 50018). The vibration frequency and acceleration are determined by a vibration controller (Tira SVC 01) connected to a power amplifier (Tira BAA 60), where the output signal is then used to control the electromagnetic shaker. An accelerometer attached to the stage measures the vibrations and the displacement and feeds it back into the vibration controller for consistent operation. The energy harvester's output is connected to an oscilloscope (InfiniiVision DSO-X 2024A) with a 1 MΩ input impedance for measuring the corresponding voltage.

Figure 4(a) presents the fabricated harvester attached to the shaker. Measurements are accomplished by sweeping the vibration frequency from 10 Hz to 23 Hz (which is in the range of the ambient vibrations) at an acceleration of 1.0 g and measuring the harvester's output voltage. Figure 4(b) shows the harvester's transient response when the frequency of the shaker is fixed at 12 Hz. Despite this low vibrational frequency, the proposed harvester's output voltage has a frequency of 333 Hz, and it corresponds to the resonant frequency of the HF beam. In other words, as long as the frequency of the vibrations is within the bandwidth of the system, the introduced design up-converts this frequency to the resonant frequency of the HF beam. The output voltage peaks occur when the HF beam can no longer follow the LF beam and is retracted back to its natural position.

Figure 4(c) and (d) show the comparison between the response of the proposed harvester to the conventional single-beam architecture (i.e., Figure 1(c)). It has the same dimensions as the LF beam, and the response was measured at its resonant frequency (12.2 Hz) and at 18 Hz, which lies outside its bandwidth. The conventional design offers a peak voltage of 9.85 V when operating at its natural frequency of 12.2 Hz. However, this voltage quickly drops to below 1
V once the oscillating frequency is different from the resonant. All the while, the proposed architecture’s absolute peak voltage remains somewhat unchanged for a broader range of frequencies.

Figure 4(e) compares the peak voltage and bandwidth performance of the introduced harvester with a conventional single-beam harvester. As shown, the proposed harvester offers a higher peak voltage for a wider bandwidth compared to the single-beam harvester. The conventional harvester has a peak voltage of 9.85 V at 12.2 Hz and a bandwidth of 0.34 Hz. On the other hand, the proposed harvester offers an average peak voltage of 14.83 V for a bandwidth of 11.39 Hz (i.e., ranging from 10.77 Hz to 22.16 Hz), with a maximum of 16.28 V at 21.5 Hz. For example, at the resonant frequency of the single beam architecture (i.e., 12.2 Hz), the proposed design offers an estimate of a 50.15% higher peak voltage of 14.79 V (given that at 12 Hz and 12.5 Hz, the generated voltages are 14.87 V and 14.67 V, respectively), compared to 9.85 V for the single beam. The enhanced bandwidth is 33.5 times the bandwidth of conventional architecture, which is an increase of 3250%.

Figure 4(f) shows the average power of both approaches using the $P=V_{rms}^2/R$, where the $P$ is the average power, $V_{rms}$ is the square root of the mean of the transient voltage squared, and $R$ is the load (i.e., 1 MΩ). The power achieved by the single beam is greater than that of the magnetic frequency up-converter; yet, this is only for a limited, narrow bandwidth centered around the natural frequency of the conventional harvester. However, the proposed architecture offers higher power for a broader range of vibrational frequencies.

Since the system by nature contains both HF and LF beams, both can be used to harvest energy, and one can receive the benefits of both beams. By adding a transducer to the LF beam, both beams' power can be summed up, resulting in maximum theoretical power. This superposition of the output power can also be seen in Figure 4(f).

Table 1 compares the proposed vibrational harvester's performance with the state-of-the-art beam-based LF frequency up-conversion vibrational harvesters. The measured
The first four designs use PZT as a transducer instead of PVDF, which compromises the devices' durability, as PZT is fragile. They also have low normalized bandwidth of operation. The fifth architecture uses PVDF and offers a high normalized bandwidth by utilizing multiple magnets for the frequency up-conversion, allowing extremely low frequencies to be detected and up-converted. Their design, however, produces a low peak voltage even when using a PVDF sheet of large dimensions, as the size of their beam is larger than that of our design; thus, it oscillates at a lower frequency. The proposed contactless magnetic frequency up-converter is durable and offers a large normalized bandwidth of 0.692 and a large peak voltage of 16.28V. This amplification is due to the design focusing on increasing the frequency and the displacement of the beam; by having the LF beam oscillate freely, it attracts the HF beam to a large displacement. The proposed system also operates at low acceleration levels and frequencies while using the smallest volume of a piezoelectric transducer, compared to the other devices. Note that approaches utilizing permanent magnets instead of soft-magnets have lower resonant frequencies (e.g., Zhewei Chen et al. has a resonant frequency of around 40 Hz), due to the added weight of the permanent magnets and, accordingly, offer lower output voltage.

**Experimental Section**

The LF beam is made of polystyrene and is 10 mm × 30 mm × 0.27 mm, with an extra 10 mm in length attached to the bulk and a 4 mm cube magnet (NdFeB) attached to its free end. The soft magnet amorphous metal used for the HF beam is Metglas® 2605SA1. It is 10 mm × 10 mm in size with a thickness of 0.05 mm, having an extra 10 mm to attach it to the bulk.

The used piezoelectric transducer is a PVDF sheet (PIEZOTECH®, poled and metalized Cr/Au) of size 7 mm x 11 mm and a thickness of 0.02 mm and is attached on top of the HF beam using a thin layer of super glue (ALTECO). PVDF was used instead of PZT for its flexibility as a polymer, compared to PZT, which has a higher piezoelectric coefficient.
The gap between both beams is 0.5 mm and was determined experimentally by varying the gap and observing the maximum output voltage.

**Conclusion**

In conclusion, the contactless magnetic frequency up-converter directly converts the low-frequency ambient vibrations into high-frequency electrical signals with wide bandwidth and high peak voltages. Unlike conventional approaches, the introduced harvester utilizes the attraction force between a permanent magnet and a soft-magnet. As a result, the harvester can operate at low-frequency conditions and low input accelerations to generate a high output voltage. Verified by measurements, the operating frequency ranges from 10.77 Hz to 22.16 Hz, with a 1.0 g acceleration. The achieved peak voltage is 16.28 V, as opposed to 9.85 V for a conventional single-beam harvester. The average power calculated is higher for 92.56% of the bandwidth. This makes the frequency up-converter a better option for harvesting a broader range of below threshold ambient vibrations.

**Supporting Information**
Supporting Information is available from the Wiley Online Library or from the author.

**Acknowledgements**
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References


[27] P. Li, N. Xu, C. Gao, Microsystem Technologies 2019, 1-10.


[31] Z. Chen, F. Zhang, X. Xu, Z. Chen, W. Li, F. Li, J. Han, H. Zhou, K. Xu, L. Bu, 2019 20th International Conference on Solid-State Sensors, **2019**.
Figure 1. a) Block diagram of a complete vibrational energy harvester that consists of a beam to capture the vibrations, a piezoelectric transducer to convert the vibrations into an AC voltage; a rectifier, and a storage element device. b) Typical behaviour of a vibrational harvester with a peak voltage at a limited bandwidth. c) Typical single-beam harvester that consists of a piezoelectric transducer attached at the maximum stress point of the beam.
Figure 2. a) Contactless magnetic frequency up-converter energy harvesting system that consists of a LF beam with a permanent magnet attached at its end, and a PVDF piezoelectric transducer attached to an HF beam that is made of a soft magnetic amorphous metal. b) As the LF beam oscillates, it attracts the HF beam and causes the transducer to generate voltage with a polarity depending on the direction of motion. c) A full oscillation cycle of the LF beam and the corresponding behavior of the HF beam. The blue glow indicates the magnet's pole that the HF beam is attracted to in each state. d) The corresponding displacement of the HF beam from its natural position and the output voltage for each state. 1: The LF beam oscillates upwards and attracts the HF beam, resulting in a positive output voltage. 2: The HF beam is released, due to its elastic force dominating the magnetic force, creating a large negative spike followed by an oscillation at its natural (resonant) frequency. 3: The LF beam oscillates downwards, attracting the HF beam again with the bottom magnet. This moves the HF beam up, creating a positive voltage spike. 4: The LF beam pulls down the HF beam, creating a negative voltage. 5: The HF beam is released, creating a large positive spike followed by an oscillation at its natural frequency. 6: The LF beam oscillates upwards, reattracting the HF beam to its top magnet, and creating a negative voltage spike.
Figure 3. a) Fabricated magnetically coupled energy harvester and b) the stable-states when the system is at equilibrium (no external vibrations). The soft magnet is attracted to both poles of the permanent magnet, thus it can have two stable-states, where it is attracted to each pole.
Figure 4. a) A photograph of the fabricated harvester fixed onto an electromagnetic shaker, with an illustration of the setup. b) Transient voltage response of the proposed harvester at 12 Hz and 1.0 g. c) Transient response of the proposed harvester compared to the conventional single beam harvester at 12.2 Hz (i.e., the natural frequency of the single beam architecture), and d) 18 Hz oscillation frequencies. The contactless magnetic frequency up-converter offers a higher peak voltage for a wide range of frequencies, while the optimal performance of the single-beam architecture is limited to a single frequency. e) Comparison of the peak voltage and bandwidth of the proposed harvester and a single-beam harvester. f) Average power calculated for both harvesters, and their superposition, showing that the power achieved by the proposed harvester is greater for 92.56% of the bandwidth.
## Table 1. Performance comparison.

<table>
<thead>
<tr>
<th>Architectures in Literature</th>
<th>3dB Frequencies (Hz)</th>
<th>Normalized Bandwidth</th>
<th>Acceleration (g)</th>
<th>Peak Voltage (V)</th>
<th>Piezoelectric Material and Dimensions (mm)</th>
<th>Advantages</th>
<th>Limitations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ping Li et al. [27]</td>
<td>60-64</td>
<td>0.065</td>
<td>1</td>
<td>9.2</td>
<td>PZT 20×25×0.2</td>
<td>Two types of harvesting are utilized, piezoelectric and electromagnetic, thus achieving higher power</td>
<td>Mechanical impact on the beam can affect the durability of the device</td>
</tr>
<tr>
<td>Manjuan Huang et al. [28]</td>
<td>42-45</td>
<td>0.069</td>
<td>0.3g</td>
<td>0.208</td>
<td>PZT 15×14×0.065</td>
<td>Compact in size</td>
<td>Mechanical impact on the beam can affect the durability of the device</td>
</tr>
<tr>
<td>Hailing Fu et al. [29]</td>
<td>21-30</td>
<td>0.353</td>
<td>1.1</td>
<td>5</td>
<td>PZT 26.5×1.5×0.1 (×2)</td>
<td>Bistable design amplifies the bandwidth</td>
<td>Large in dimension, plucking affects durability</td>
</tr>
<tr>
<td>Jinhui Zhang et al. [30]</td>
<td>76-86</td>
<td>0.123</td>
<td>0.6</td>
<td>6</td>
<td>PZT 5.5×6.8×0.15</td>
<td>Tunable frequency range</td>
<td>Mechanical impact on the beam can affect the durability of the device</td>
</tr>
<tr>
<td>Zhewei Chen et al. [31]</td>
<td>0.01-0.1</td>
<td>1.636</td>
<td>-</td>
<td>1.5</td>
<td>PVDF 100×30×0.054</td>
<td>Impact-less design enhances durability</td>
<td>Requires 6 magnets</td>
</tr>
<tr>
<td>Proposed work</td>
<td>10.77-22.16</td>
<td>0.692</td>
<td>1</td>
<td>16.28</td>
<td>PVDF 11×7×0.05</td>
<td>Impact-less design enhances durability, and offers high voltage and extended bandwidth</td>
<td>LF beam size increases when harvesting LF vibrations</td>
</tr>
</tbody>
</table>
A magnetic vibrational energy harvester is proposed. A permanent magnet is attached to a low-frequency beam attracting a soft magnet high-frequency beam. The system converts low-frequency ambient vibrations to high-frequency pulses, and with an added piezoelectric material generates an amplified output voltage. The system has an extended bandwidth of operation, all while operating at low-frequency and low acceleration conditions.

**Keyword** energy harvesting, mechanical vibrations, voltage amplification, frequency up-conversion, wideband operation

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**A Wideband Magnetic Frequency Up-converter Energy Harvester**
Supporting Information

**A Magnetic Frequency Up-converter for Wideband Energy Harvesting**

*Esraa Fakeih†, Abdullah S. Almansouri†*, Jurgen Kosel, Mohammad I. Younis, and Khaled N. Salama*†

**Supplementary Information 1: Conventional Mechanical Harvester**

Table S1 shows different mechanical energy harvesters for harvesting ambient vibrations. All the methods discussed use beams to capture the vibrations and piezoelectric transducers for the voltage generation. Each method has its advantages and limitations relating to durability, fabrication, voltage amplification, and bandwidth enhancement. In short, frequency up-conversion is the preferred method for capturing low-frequency (LF) environmental vibrations while having a durable system.
Table S1. A comparison of different methods of voltage and bandwidth enhancement in vibration energy harvesting.

<table>
<thead>
<tr>
<th>Methods of Harvesting</th>
<th>Explanation</th>
<th>Advantages</th>
<th>Limitations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single beam cantilever [1]</td>
<td>The beam is designed to oscillate at a specific frequency of vibration</td>
<td>Simple to fabricate</td>
<td>Limited bandwidth of operation</td>
</tr>
<tr>
<td>Multiple beams [2]</td>
<td>Uses beams of different lengths to enhance the bandwidth</td>
<td>Wideband operation</td>
<td>Multiple beams increase the volume of the device</td>
</tr>
<tr>
<td>Meandering beam [3]</td>
<td>Bends a long beam into a meandering structure. This lowers the spring constant, reducing its resonant frequency compared to a fixed beam of the same length</td>
<td>Lower resonant frequency</td>
<td>Complex design</td>
</tr>
<tr>
<td>Impact driven harvester [4]</td>
<td>Applies direct impact on the piezoelectric transducer (i.e., by hitting the transducer) to generate higher voltage</td>
<td>Captures LF vibrations, high voltage output</td>
<td>Susceptible to wear and tear</td>
</tr>
<tr>
<td>Rotational energy harvester [5]</td>
<td>Magnets are arranged to form a ring of low potential; when vibrations are present, a movable magnet circulates along the ring route</td>
<td>Captures LF vibrations</td>
<td>Low voltage output</td>
</tr>
<tr>
<td>Magnetic Plucking [6]</td>
<td>Magnets vibrate above a cantilever, plucking it as they pass over it</td>
<td>Captures LF vibrations</td>
<td>Low voltage output</td>
</tr>
<tr>
<td>Frequency up-conversion [7]</td>
<td>Increases the frequency by coupling long LF beams to short high-frequency (HF) beams, upconverting the environmental vibrations into high-frequency pulses, thus increasing the voltage generated</td>
<td>Durable, captures LF vibrations, high voltage output</td>
<td>Less voltage than the impact-driven method</td>
</tr>
</tbody>
</table>
Supplementary Information 2: Amorphous Metal Characterization

Permanent magnets are materials that have a strong magnetization without the need of an external magnetic field; they can be ferromagnetic or ferrimagnetic. Soft magnets, however, require an external magnetic field to become magnetized. They exhibit low coercivity, meaning it is easier to change their magnetization polarities easily. Metglas® 2605SA1 is an amorphous soft magnet that exhibits low core losses and high permeability. It has a high saturation point of about 1.56 T compared to other ferrite cores (~ 0.3 – 0.4 T).

Figure S1 shows the magnetization curves of the Metglas® 2605SA1, which was achieved by sweeping the magnetic field from -100 mT to 100 mT across a 2.5 × 2.5 mm sample. The measurement results were achieved by using a Vibrating Sample Magnetometer (VSM). The Metglas® was placed into a sample-holder and secured using a silicon grease. It was then set to oscillate at 83 Hz with a 1 mm amplitude. The results show the behavior of a typical soft magnet, giving a saturation magnetic field of 1.33 T, and a high slope at the origin, with minimum hysteresis loop. The permeability of the material is high (i.e., the slope at the origin) and equals 84334. This increased permeability translates to a higher attraction force between the soft-magnet and the poles of the permanent magnet in the proposed contactless magnetic frequency up-converter energy harvester.
Figure S1. Magnetization curve of the amorphous-metal soft magnet (Metglas 2605SA1) shows a high saturation field, minimum hysteresis loop, and maximum permeability (i.e., the slope near the origin).
Supplementary Information 3: Piezoelectric Materials

Piezoelectric transducers are the interface between the electrical and the mechanical environment. They consist of polarized perovskite crystals that have a net dipole moment. Compressive or tensile stresses on the material change the dipole moment, creating a voltage across the material. Likewise, applying a voltage across the material changes the shape of the material.

The piezoelectric coefficient $d_{ij}$ demonstrates the ratio of the electric displacement to the stress applied.$^{[12]}$ This coefficient changes depending on the direction the voltage/stress is applied, where $i$ is the direction of the electric field, and $j$ is that of the stress. For example, $d_{31}$ is the coefficient when the voltage is applied in the direction of polarization (3), and the stress is observed in the plane perpendicular to the polarization (1 and 2). The coefficient $d_{33}$ would be when both the voltage/stresses are applied/observed in the direction of polarization.

Different types of materials are available, out of which the two most common types are PZT and PVDF. The main difference between them is the first is a ceramic material, whereas the second is a polymer. They each have their advantages and disadvantages (Table S2) and can be useful in different applications.

PZT being a ceramic material, is very brittle and stiff, making it challenging to handle longtime stresses; regardless, it has a high piezoelectric coefficient. The stiffness of PZT can interfere with the dynamics of a sensing system, and so PVDF is more appropriate for that use. PVDF is a polymer, and so is well equipped to experience different stresses and strains; however, it has a lower piezoelectric constant, compared to PZT.
Table S2. Comparison between PZT and PVDF.

<table>
<thead>
<tr>
<th>Material</th>
<th>Density (kg/m$^3$)</th>
<th>Young’s Modulus (Gpa)</th>
<th>$d_{33}$ (pC/N)</th>
<th>$d_{31}$ (pC/N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PZT – 5A (PSI-5A4E)$^{[13]}$</td>
<td>7,800</td>
<td>52</td>
<td>390</td>
<td>-190</td>
</tr>
<tr>
<td>PVDF (Piezotech® FC30 – 20 µm)$^{[14]}$</td>
<td>1,780</td>
<td>1.4</td>
<td>-21</td>
<td>6</td>
</tr>
</tbody>
</table>
References


