FLEXIBLE POLYIMIDE FILM TECHNOLOGY FOR VIBRATION ENERGY HARVESTING

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Abstract: In this paper we present recent developments of an electromagnetic vibration energy harvester based on micro-machined flexible polyimide films and planar micro-coils. A range of different prototype resonator structures were successfully fabricated with resonance frequencies in the range of 200 Hz to 400 Hz. A fully assembled prototype generator device produced an output power of 5 µW (70 mV at 1000 \(\Omega\)) of peak power from a harmonic input excitation of 9g (15 µm amplitude at 390 Hz).

Keywords: Energy harvesting, micro-coil, polyimide, electromagnetic vibration transducer

INTRODUCTION

Microscale power generation systems have been extensively investigated over more than one decade, exploring a variety of designs and materials \([1, 2]\). The use of flexible polymer materials to implement resonator structures for vibration induced power generators has also been considered \([3, 4]\). For instance, Sari et al uses parylene as a flexible polymer material for fabricating the resonator structures \([4]\). Their prototype device measures 8 mm x 9.5 mm x 5 mm in size and uses 20 parylene cantilevers and a permanent magnet. Measurements show that about 15 nW (8.75 mV @ 5 k\(\Omega\)) could be generated from an harmonic input excitation of 73 g (5.1 kHz).

However, the potential of vibration generators completely manufactured from polymer films in the form of large-area flexible sheets, which could be applied to large vibrating surfaces, has not been investigated. Since the technology of flexible electronics printed on polymer film substrates has become well established, the development of a low-cost polymer multi-layer generator-foil based on the lamination of different functionalized polymer sheets is therefore self-evident. In this paper we focus on the implementation of polyimide as a functional material for manufacturing resonator structures for polymer vibration generators. In addition, the use of magnetically functionalized SU-8 for the development of electromagnetic vibration generators is also investigated.

DESIGN

In the first phase of this development a prototype device-family is implemented with a size of 18 mm x 18 mm x 2 mm (Fig. 1). At this stage glass substrates are used, first to provide a technology compatible support for the micro-coil fabrication and second to realize a robust housing for the generator. At a later stage the glass substrates can be replaced by polymer sheet materials. As shown in Fig. 1 the polymer vibration generator is made of 4 layers: the bottom substrate with an SU-8 layer (150 µm), a polyimide resonator membrane (50 µm), a magnetically functionalized SU-8 layer (200 µm) and the top substrate with an SU-8 layer (150 µm). The top substrate also contains the micro-coil, which is made of three separate layers. During fabrication a particular problem occurred with respect to the material combination of polyimide and magnetically functionalized SU-8. Therefore, a permanent magnet of 6 mm diameter and 1 mm height was used to provide the magnetic field. This still allows us to focus on the characteristics of the polyimide as a flexible material for the resonator structure.

![Fig. 1: Exploded view schematically showing the assembly of the polymer vibration generator.](image-url)
Table 1: Design variants of the resonator structure.

<table>
<thead>
<tr>
<th></th>
<th>Design A</th>
<th>Design B</th>
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<tbody>
<tr>
<td>Beam length</td>
<td>5 mm</td>
<td>5.3 mm</td>
</tr>
<tr>
<td>Beam width</td>
<td>3 mm</td>
<td>2 mm</td>
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<tr>
<td>Diameter</td>
<td>7 mm</td>
<td>12 mm</td>
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<table>
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<tr>
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<th>Design C</th>
<th>Design D</th>
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<tbody>
<tr>
<td>Beam length</td>
<td>5.3 mm</td>
<td>5.7 mm</td>
</tr>
<tr>
<td>Beam width</td>
<td>2 mm</td>
<td>1 mm</td>
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<tr>
<td>Diameter</td>
<td>7 mm</td>
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In Table 1 the different designs of the resonator structure are summarized. The beam width and the diameter of the inner disk-like structure were varied. The beam length varies only slightly due to the different beam widths. The different disk dimensions were chosen in order to realize magnetic areas of different sizes.

**FABRICATION**

**Micro-coil**

The integrated micro-coil (Fig. 2a) is made of 2 copper layers, which are isolated from each other by a polyimide layer. The first copper layer defines the contact paths including the contact pads for the micro-coil and the bond pads. The second copper layer defines the micro-coil body. Two vias in the polyimide layer provide interlayer connectivity between the contact pads and the micro-coil. The two copper layers were fabricated utilizing an electroplating process where copper is deposited into a mould. The mould was fabricated from a dedicated photo-resist (AZ 9260) on a glass substrate. The micro-coil consists of 300 turns with a track width of 9 µm and a spacing of 11 µm between the tracks (see Fig. 2b). The internal resistance was 840 Ohm.

**Resonator**

The resonator structures were fabricated on a glass substrate by spin-on technology and photolithography. First, a 50 µm layer of polyimide (HD4100, HD Microsystems) is deposited and structured by photolithography. Second, a 200 µm layer of magnetically functionalized SU-8 is deposited and also structured by means of photolithography. The results are shown in Fig. 3a. When releasing the resonator structures from the substrate by a wet chemical etch step, the material compound deforms significantly in such a manner, that the resonator structures cannot be used any further. We therefore replaced the magnetically functionalized SU-8 layer temporarily by a NdFeB permanent magnet as shown in Fig. 3b.
Fig. 3: Fabricated resonator structures: a) Polyimide membrane with magnetically functionalized SU-8 on a glass substrate (resonator is not suspended); b) Suspended polyimide resonator with NdFeB magnets on SU-8 frame, which sits on a glass substrate.

Generator

Prototypes of completely assembled generator devices including a polyimide resonator with a permanent magnet and a micro-fabricated micro-coil are shown in Fig. 4. The different components of the device were assembled using an epoxy adhesive.

DISCUSSION

Polyimide resonator with permanent magnet

Fig. 5 shows the frequency response of the different resonator designs as listed in Table 1. A laser-vibrometer was used to measure the out-of-plane displacement amplitude. The position and height of the resonance peak varies with the design of the resonator geometry. In general, design A and C show the largest displacement amplitudes (e.g. about 100 µm at 5 µm excitation amplitude). These are the designs with the smaller disk size. Designs B and D have a larger disk size and therefore mechanical damping due to viscous damping is larger.

This results in smaller displacement amplitudes as shown in Fig. 5.

The position of the resonance peak is primarily dependent on the stiffness of the resonator structure (assuming a constant mass). Design A with a beam width of 3 mm shows a resonance frequency of ca. 400 Hz. In contrast, design D with a beam width of 1 mm exhibits a resonance frequency of ca. 230 Hz. Moreover, a non-linear (hardening-effect) frequency response characteristic is recognized for design A and C. This is due to the fact that the resonator designs are based on double clamped structures that stiffen when out-of-plane displacements occur.

For each design four resonator devices identical in construction were characterized. The results are summarized in Fig. 6. It is noticeable that the median deviation, which is ca. ±45 Hz for each design, is significantly high. We assume that this is due to the assembly process. As described above, the polyimide resonator membranes were bonded by means of an epoxy adhesive that cures at a temperature of 80°C.

Fig. 5: Frequency response of resonator designs for different excitation amplitudes
Due to the different thermal material properties of polyimide, SU-8 and epoxy resin, the induction of thermal stress cannot be excluded. For large scale production a lamination process may be used for bonding the different polymer sheet components of the generator. This may improve the reproducibility of the devices with respect to their resonance frequency. When considering a large-area generator-foil with a large number of generator devices, a broad variation of the resonance frequency may be even an advantage. This is because a broad band characteristic would be the consequence.

Complete generator device

In Fig. 7 experimental results are show for a prototype generator device incorporating a resonator design A. The device is able to generate about 5 µW (70 mV, 1000 Ω) of peak power from a harmonic input excitation of 9g (15 µm amplitude, 390 Hz). A power of ca. 1 µW is generated when the device is excited with 1.1 g (2 µm, 370 Hz). The frequency response with respect to the power output seems rather broad. Mechanical damping due air displacement may be larger for the completely assembled device (Fig. 4) than for the non-packaged resonator structures (Fig. 3b). When considering a square meter of generator-foil accommodating thousands of optimized generator devices, a total output power in the range of several tens to several hundreds of mW may be achievable.

CONCLUSION

In this experimental study the applicability of polyimide and magnetically functionalized SU-8 was investigated. We found that polyimide is suitable for the construction of resonating membrane structures. However, the combination of polyimide and magnetic SU-8 induced some technological problems during fabrication. Though, the lamination of different polymer materials should be feasible. In this respect magnetically functionalized layers may be bonded on top of polyimide layers to produce an oscillating magnet.

We also found that the assembly process has a significant influence on the reproducibility of the device parameters, e.g. the resonance frequency. Moreover, a larger number of turns is required for the micro-coil in order to increase the output voltage.

Further work will involve the evaluation of printed multi-layer micro-coils on polymer material and the development of magnetic functionalized polyimide.

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REFERENCES


