1. Introduction

An energy harvester is an attractive energy source for supplying power to micro-devices such as small wireless sensor nodes for future ubiquitous networks.[1–3] In particular, a microelectromechanical system (MEMS) based vibrational energy harvester has been intensively researched with a view to node miniaturization [4, 5]. Three types of vibrational energy conversion have been studied, namely piezoelectric,[6–8] electromagnetic,[9–11] and electrostatic [12–14] induction. Electrostatic induction is a promising mechanism because it is compatible with the CMOS-LSI process.[15] Figure 1 shows the fundamental mechanism of current generation by electrostatic induction in the energy conversion region of a slit-and-slider structure.[16] Fixed negative charges in an electret film induce counter positive charges in movable and fixed electrodes as shown in Fig. 1 (a). In the initial state, the fixed electrodes and movable electrodes keep the state aligned vertically. A number of unit cells for energy conversion are aligned across the movable plate in a horizontal direction for earning the conversion in one movement period. Figure 1 (b) and (c) show the mechanism in the unit cell. In Fig. 1 (b), when a movable electrode is displaced laterally by an external force such as a vibration from surrounding environment,[1–3] the induced charges are transferred between the movable and fixed electrode through an external load. In Fig. 1 (c), when the movable electrode is re-displaced to the initial position, the induced charges are transferred again. Therefore, in the external load which connects the movable electrodes to the fixed electrodes, electrical current is generated due to the displacement as shown in Fig. 1 (b) and (c). One issue is that the generated output becomes small corresponding to the miniaturization of the energy harvester. There are certain ways of dealing with this issue, including: (1) increasing the number of pairs of movable and fixed electrodes, (2)
increasing the fixed charge of the electret, and (3) narrowing the clearance of the gap between the movable and fixed electrodes as shown in Fig. 1 (c). For the first approach, we have proposed a synchronized vibrational array device and obtained a nano-ampere level current in a mm³-sized energy conversion region.[16] For the second approach, some groups have reported composite electrets to increase the charge.[17–19] The third approach has not been confirmed experimentally although some groups have indicated its effectiveness by downsizing the gap to micron level.[20–22]

In the previous paper, we have proposed a novel method for narrowing the gap of a millimeter-sized slit-and-slider structure by nested structure in an electrostatic vibrational MEMS energy harvester.[23] In this paper, we show a fabrication process of the nested structure. A micron level gap is achieved by using a nested flip-chip assembly. A simulation using finite-element-method is shown to assure the mechanism of current generation with gap of micron level. Parasitic capacitance including the measurement system is discussed to introduce an equivalent model. The structural normalized parameter is discussed to estimate the effect of gap narrowing. These measurement, simulation, and discussion showed gap narrowing is effective in enhancing current generation.

2. Experimental Procedure

Figure 2 shows the basic components of the slit-and-slider structure of a vibrational energy harvester that we have already proposed.[16] This structure consists of a slit chip (upper chip) and a slider chip (lower chip). The slit chip contains a charged electret film, a fixed electrode, and a supporting substrate. The slider chip contains a lower wall and a movable part, which consists of a movable electrode suspended by springs through anchors, on a substrate. The features of this structure are as follows: (1) it ensures an arbitrary gap between the fixed and movable electrodes by controlling the height of two walls that separates the slit and slider chips, (2) it integrates composing elements used for vibrational energy harvesting in slit and slider chips (3) it uses a wall to protect the movable part on the slider chip from various external stimulations, such as a dust, moisture, and other damage. Each chip is connected by means of two walls using a conventional flip-chip assembly.
assembly, which has often been employed in MEMS device fabrication.[24–27] As regards the structure of such MEMS devices, a lot of isolated bumps are formed to connect the upper chip with the lower one. That is, there is a drawback in that many interspaces between the upper and lower chips are open to the outside environment. On the other hand, our proposed structure has the merit that the walls work both to adjust the gap between the two electrodes and to provide protection from the external stimulations since the wall completely surrounds the movable part.

The slit-and-slider structure is fabricated in three steps: the fabrication of the slider chip with the MEMS structure, the fabrication of the slit chip, and the flip-chip assembly of the slit-and-slider chip. The procedure for fabricating the slider and slit chips is shown in Fig. 3. Figure 3 (a) shows the top view of the slider chip. To realize the slider chip, the movable structure, springs, walls, and stoppers, which are structures to prevent the springs from overmuch displacement of the movable plate, were fabricated on interconnection layers formed on a Si wafer by employing a thick-multilevel interconnection technique. Figure 3 (b) shows the formation of the interconnection layer as the cross section for the A-A’ and B-B’ line in Fig. 3 (a). For the slider chip, interconnections were fabricated by electroplating a 0.5-μm-thick gold film on a silicon substrate covered with a 1-μm-thick SiO2 film formed by thermal oxidation. Au and Ti layers were deposited as the seed and adhesive layers, respectively. The SiO2 film was deposited by plasma-chemical vapor deposition (P-CVD) as the insulator. The via-holes on the interconnections were formed by photolithography and reactive ion etching. Figure 3 (c) shows the formation of 1st layer. Then, the wall stopper, anchor, and pad were also fabricated by gold-electroplating. Each structure is 10 μm thick. Next, a layer of photosensitive polyimide was spin-coated and patterned by photolithography with the same height as that of the electroplating layer for the first sacrificial layer. It was cured at 310°C for 1 h. Figure 3 (d) shows formation of 2nd layer. The movable plate, springs, stopper, and anchor were then formed. Each structure is 25 μm thick. After that, a second sacrificial layer with a 25 μm thickness was formed in the same manner as the first layer, and 20-μm-thick movable electrodes and stopper were fabricated [Fig. 3 (e)]. After that, the first and second sacrificial layers were removed by ozone ashing. Thus, the movable plates were released and suspended with the springs over the substrate [Fig. 3 (f)].
Figure 3 (g) shows the top view of the slit chip, on which the fixed “slit” electrode and wall acting as the spacer are fabricated. Figure 3 (h) shows the fabrication of the slit chip. The fixed electrode and wall were also fabricated by gold-electroplating on a silicon substrate. The fixed electrode and wall are 1 \(\mu\)m and 20 \(\mu\)m thick, respectively.

Figure 4 shows the flip-chip assembly fabrication process. The flip-chip assembly technique includes a metallurgy bonding method[28] and an adhesive bonding method.[29] In this case, the adhesive bonding method is used because it is effective in suppressing the influence from the dispersions in height of wall, which derives from the process variation with electroplating. For adhesion transfer, the direct transfer method is adopted because of its simplicity [30, 31]. For the chip bonding, silver paste is utilized as a conductive adhesive to obtain electrical contact between the two chips. The process is explained in detail below. First, silver paste (Model: QMI-516, Hysol co. LTD.), whose viscosity was 8000 cP at room temperature, was applied to a stage. Next, the surface of the paste was flattened with a squeegee [Fig. 4 (a)]. The slit chip was flipped and then inserted into the flattened paste with a few microns clearance between the top of the fixed electrode and the surface of the paste under a weight of 5 gt/100 \(\mu\)m\(^2\) for 0.1 seconds [Fig. 4 (b)]. Then, the paste was transferred to the surface of the wall for the slit chip [Fig. 4 (c)]. The slit chip and slider chip were adjusted by using mark patterns [Fig. 4 (d)] and then pre-jointed under a weight of 5 gt/100 \(\mu\)m\(^2\) at a temperature of 115°C for 60 seconds. The experiment was carried out in a clean room which was controlled for temperature as 25°C \(\pm\) 3°C, and humidity as 30% \(\pm\) 10%. They were subsequently cured at 150°C for 30 minutes in a nitrogen atmosphere [Fig. 4 (e)].

There is a fabrication difficulty involved in reducing the gap between the fixed and movable electrodes. When the wall on the slit chip is lowered, the paste adheres to an undesired region, which causes an electrical short, as shown in Fig. 5 (a). To solve this problem, a nested flip-chip assembly technique is proposed. This structure nests a convex slider chip with a concave slit chip, as shown in Fig. 5 (b). This approach is effective in reducing the gap while preventing the possibility of an electrical short because the paste stays close to the wall of the upper chip.
3. Results

Figure 6 shows scanning electron beam microscope (SEM) images of the fabricated MEMS structure on the slider chip. Figure 6 (a) shows a SEM image of the electrical connecting pad and wall after the silver paste has been transferred as shown in Fig. 4 (c). This image also indicates that the silver paste is applied selectively to only the desired surface of the pad and the wall. The movable plate remains floating to avoid sticking to the substrate as shown in Fig. 6 (b). Figure 7 (a) shows cross-sectional SEM images of the fabricated slit-and-slider structure and Fig. 7 (b) shows a close-up view of Fig. 7 (a). These cross sections of the structure are obtained by an ion milling. These SEM images suggest that horizontal alignment is successfully controlled. These images show that the clearance of gap is obtained since the movable plate, which supported by springs through the anchors as shown in Fig. 6, is floating between the slit and slider chip. Although each edge of the movable plate looks distorted, this distortion is originated from the ion milling whose beam shape is cylindrical. Therefore, it has no effect on the characteristics. Figure 7 (c) shows a cross-sectional SEM image of the walls after the flip-chip bonding shown in Fig. 4 (e). It shows that the wall is jointed by means of silver paste. The thickness of the silver paste was 3 μm. As for the structural dimension of the slider chip, the height of the 1st and 2nd layer of the wall are 10 μm and 25 μm, respectively. While, as for the slit chip, by controlling the height of the wall on the slit chip, the gaps between the slit and slider chips can be varied from 31.0 to 3.8 μm. As for the gap of 3.8 μm, this is a limited value because of the accuracy for our fabrication process.

Figure 8 shows an experimental result for shear
strength evaluation with a bonding tester (Model: PTR-1000, Rhesca Co. LTD.). The fabricated chip was fixed on the tester stage, and then the position of the shearing tool was calibrated to hold the lateral face of the slit chip. The driving speed of the tool was set at 0.2 mm/sec. The shear strength at the interface between the walls of the slit and slider chips was evaluated as shown in the inset in Fig. 8. In Fig. 8, the shear strengths of 12 samples exceeded 1 kgf/mm², which is also the guaranteed value of the silver paste’s bonding strength.[32]

Figure 9 shows the experimental setup for measuring current generation. An electret film, ethylene-tetrafluorinated ethylene copolymer (ETFE), is sandwiched between the top of the MEMS vibrational device and a metal plate. We use a 100-μm-thick ETFE film whose permittivity and dielectric tangent are 2.6 and 0.0008 at 1 kHz, respectively. The film was subjected to a DC corona discharge at a bias voltage of -10 kV and room temperature. The average potentials on the surface and rear side of the charged film around the area above the movable plate were about -900 and +780 V, respectively. From these potentials, the charge densities were calculated with\[
\sigma = \epsilon_0 \frac{\varepsilon}{d} V, \quad (1)
\]
where \(\sigma\) is the charge density, \(\epsilon_0\) is the permittivity of vacuum, \(\varepsilon\) is the relative permittivity of the ETFE, \(d\) is the thickness of the electret film, and \(V\) is the potential.

The fixed electrodes and metal plate were directly grounded. The movable electrodes were also grounded through the lock-in amplifier which has an impedance of 1 kΩ. The lock-in amplifier detected the current signal synchronized with an input vibrational reference signal. The external vibration frequency was swept upwards from 1,200 Hz to 1,450 Hz, while keeping the acceleration constant at 6 m/s², as found in practical environments.[33] The measured current versus the gap is plotted in Fig. 14 (a). The measured AC current shows that the peak is at around 1.4 kHz, which is consistent with the structurally expected resonant frequency. The characteristics have been shown in previous paper as.[16] The maximum value is 2.3 nA at 3.8 μm, and this experimental result indicates that narrowing the gap boosts the current.

4. Discussion
4.1 Current generation

The current generation was calculated to confirm the experimentally obtained gap narrowing effect theoretically. Since an electric current is defined as the flow of an electric charge through an electrical conductor per unit time, the mean value of the current, \(I\), is expressed as

\[
I = \frac{1}{T} \int_0^T \left( \frac{dQ}{dt} \right)^2 dt = \frac{1}{2\pi} \int_0^{2\pi} \left( \frac{dQ}{d\theta} \right)^2 d\theta = 2\pi f \left( \frac{dQ}{d\theta} \right). \quad (1)
\]

where \(T\), \(Q\), \(t\), \(f\), and \(\theta\) are the vibration period, charge, time, frequency and phase, respectively.[34] Here, a finite-element-method (FEM) analysis is conducted to solve the charge change \(\Delta Q/\Delta \theta\). Figure 10 shows a top view of the movable structure for the analysis. The view shows the image of a layer consisting the movable electrode and the movable plate. The movable plate is 1 mm². The analytical simulation area was divided as 5 units according with typical shapes. Figure 11 shows a cross section of the one of the periodic structure of unit 1 as for a moving state of a movable electrode. A substrate, fixed electrode, movable electrode, and movable plate are arranged. In addition, we assumed a charged electret with a metal plate was on the
slit chip in the same way as the experimental setup in Fig. 9. The electret was assumed to be a double layer charged dielectric film for upper and lower charged layers 5 \( \mu \text{m} \) deep from each surface.[34] The volume charge densities were estimated to be \(-4.14 \times 10^{-5} \text{ pC/\mu m}^3\) and \(3.59 \times 10^{-5} \text{ pC/\mu m}^3\). These values were calculated to divide the area charge densities of \(-20.7 \text{ nC/cm}^2\) and \(17.9 \text{ nC/cm}^2\) by 5 \( \mu \text{m} \), respectively. All the electrodes, the movable plate, and the metal plate were grounded, while the substrate of slit chip was kept floating. Table 1 shows parameters for the FEM analysis corresponding to the elements in Fig. 11. With these parameters, a potential and charge were calculated at each \( x \) displacement. Figure 12 shows a calculated two-dimensional distribution of potential for the periodic structure in unit 1 when the displacement is 20 \( \mu \text{m} \). In the unit at both left and right sides of the area, cyclic boundary conditions are applied. In the other units shown in Fig 10, similar constructions were calculated. The calculated values at each part were finally summed up to obtain the results for the whole three-dimensional structure. We estimated each charge change as the difference from the charge at \( x = 0 \) \( \mu \text{m} \). Here, we assumed the displacement to be 24 \( \mu \text{m} \), since it should be less than 30 \( \mu \text{m} \) between the movable plate and the stopper, and a damping force caused by the charge change is unconsidered. The current is

![Fig. 10 A top view of the movable structure for the analysis.](image)

![Fig. 11 A cross section of the unit 1 as for a moving state of a movable electrode.](image)

| Table 1. Parameters for the FEM analysis in corresponding with the elements in Fig. 11. |
|-----------------------------------------------|
| Electret                        | Top charge density | \(-4.14 \times 10^{-5} \text{ pC/\mu m}^3\) |
|                                | Bottom charge density | \(3.59 \times 10^{-5} \text{ pC/\mu m}^3\) |
|                                | Relative permittivity | 2.6 |
| Substrate (Si)                  | Thickness           | 625 \( \mu \text{m} \) |
|                                | Relative permittivity | 12 |
|                                | Conductance         | 0 |
| Fixed electrode                | Thickness           | 1 \( \mu \text{m} \) |
|                                | Width               | 7.5 \( \mu \text{m} \) |
|                                | Pitch               | 60 \( \mu \text{m} \) |
| Gap                            |                      | 20 \( \mu \text{m} \) |
| Movable electrode              | Width               | 15 \( \mu \text{m} \) |
|                                | Height              | 20 \( \mu \text{m} \) |
obtained by introducing this charge change into Eq. (1). Here, phase $\theta$ is obtained by translating the displacement $x$ of a movable electrode with Eq. (2). Figure 13 shows the calculated result on the charge change for displacement. For the periodical change of the displacement, the total charge change was 0.193 pC. From this figure, periodical $\Delta Q/\Delta \theta$ is estimated as 0.142 pC. Then, the current was estimated at 1,430 Hz to be,

$$I = 2\pi f \left( \frac{dQ}{d\theta} \right) = 2\pi \cdot 1430 \cdot 0.142 = 1.28 \text{ [nA]}.$$  

(3)

The tendency of the calculated result, as shown in Fig. 14 (b), is similar to that of the experimental result, but they are both larger than the measured result. The discrepancy might be related to the different values between analytical and experiment. The actual $Q$ value of an amplitude for movable plate is attenuated by damping for the viscosity of air in a micro fluidic region in addition to the damping force caused by the great charge change that accompanies the gap narrowing.[35] A further study is needed to consider this interpretation in detail.

4.2 Parasitic capacitance

For an energy harvester of an electrostatic type, it is important to reduce the parasitic capacitance for improving output.[2] Figure 15 shows an equivalent circuit model of the system including the parasitic capacitance. The model derived by Barstch et al. can be described as a voltage divider of the inertial source resistor $R_i$ and the load $R_L$.[36] It is considered that the parasitic capacitance $C_p$ might be connected in parallel for the external load.[36, 37] In the model, the generated current $i_{ges}$ through not only $R_L$ as $i_L$ but also $C_p$ as $i_p$. In our experiment, the current $i_L$ is detected with the lock-in amplifier. In next stage, a contribution of the parasitic component for a generated current is discussed.

Figure 16 shows a schematic of various parasitic capacitances in the slit-and-slider structure. There are four parasitic capacitances: (1) $C_{p1}$ is the capacitance between the movable and fixed electrode. The capacitance includes an influence of fringe fields between them, and the fringe field changes with the displacement of the movable electrode. (2) $C_{p2}$ is the capacitance between the movable plate and the substrate. (3) $C_{p3}$ is the capacitance between the side of the movable plate and the stopper, which works as a side electrode to detect the capacitance $C_{p3}$. (4) $C_{p4}$ is the
capacitance in the coaxial cables for a measurement. Table 2 shows estimated values for the parasitic capacitances. \( C_{p1} \) was estimated by the FEM analysis as shown in the subsection 4.1. \( C_{p2} \) and \( C_{p3} \) were also estimated by calculations with the size of structures and material constant. \( C_{p4} \) was applied as value of the 1 m cable. In these values, \( C_{p4} \) is most dominant. We calculate a ratio of detected current \( i_L \) with the lock-in amplifier to the true current \( i_{ges} \) of the generator. From the circuit in Fig. 15, the generator current \( i_{ges} \) and voltage applied on \( R_L \) can be described:

\[
\begin{align*}
  i_{ges} &= i_L + i_p, \\
  R_L i_L &= -j \frac{1}{\omega C_p} i_p,
\end{align*}
\]

where \( \omega \) is angular frequency. Here, a relation is obtained to solve Eqs. (4) and (5):

\[
\frac{|i_L|}{|i_{ges}|} = \frac{1}{\sqrt{1 + (\omega R_L C_p)^2}}.
\]

In this case, the resonant frequency of the movable part and the impedance of the lock-in amplifier are applied:

\[
\frac{|i_L|}{|i_{ges}|} = \frac{1}{\sqrt{1 + (2\pi \cdot 1430 \cdot 1000 \cdot C_p)^2}}.
\]

The formula is plotted as shown in Fig. 17. This graph means a ratio of \( i_L \) to \( i_{ges} \) for the parasitic capacitance. In our case, since the value of the most dominant parasitic capacitance is 100 pF, the ratio is 0.99, that is, the parasitic component is negligible in this study. This is the advantage of low impedance current measurement by a lock-in amplifier.

### 4.3 Power output

In this subsection, two indices are introduced to compare the present device with our previous device.[34] First, the harvester effectiveness is introduced from[38, 39] as

\[
E_H = \frac{\text{Useful Power Output}}{\text{Maximum Possible Output}} = \frac{\text{Useful Power Output}}{\frac{1}{2} Y_o Z_i \omega^3 m},
\]

\[
= \frac{\text{Useful Power Output}}{\frac{1}{2} a Z_i \omega m},
\]

where \( a, Y_o, Z_i, \omega, m \) are acceleration, amplitude, maximum displacement, angular frequency of source motion, proof mass respectively. The useful power output of a harvester is obtained from[34] as

\[
P_{\exp} = R_L F^2.
\]
Here, to increase the useful power output, an optimized impedance matching of an external load is important. In this case, the difference between this structure and our previous device[34] is the gap between the movable and fixed electrode for the structure. To compare the difference, the same setup with the lock-in amplifier was applied. Although an increase of the parasitic capacitance accompanied with changing the structure is considered, it is ignorable since the C_p1 of the structure is adequately smaller than the C_p2 of the measurement setup. Therefore, it is assumed that the parasitic capacitance for the electret charge and structure is separated as expressed in Eq. (13),

\[ S(f, R_L) = \frac{d + \varepsilon_E (g + 2nfA_{max}R_L\varepsilon_0)}{nfA_{max}2\sigma R_L}, \]

where the parameters n, f, A_{max}, d, \varepsilon_E, g, and \varepsilon_0 denote the number of electret-counter-electrode-pairs, frequency, maximum overlap area, surface charge density of electret layer, thickness of electret layer, permittivity of electret, gap between electrodes, and permittivity of vacuum, respectively. We define a new index S(f, R_L) as

\[ V = \frac{\sigma}{S(f, R_L)}, \]

\[ P = \frac{V^2}{R_L} = \frac{\sigma^2}{R_L S(f, R_L)}, \]

where

\[ S(f, R_L) = \frac{d + \varepsilon_E (g + 2nfA_{max}R_L\varepsilon_0)}{nfA_{max}2\sigma R_L}. \]

S(f, R_L) has a unit of capacitance per unit volume (F/m³). When S(f, R_L) is smaller in Eq. (12), the voltage is larger for a fixed amount of d. This means that S(f, R_L) is a kind of a parasitic capacitance for the electret charge and smaller S(f, R_L) makes use of the electret charge d to produce power as shown in Eq. (12). Hence, the effect of charge and structure is separated as expressed in Eq. (13),

| Table 3 | Calculated useful power output. |
|---------|---------------------------------|
| Condition | I [A] | R_L [Ω] | \( P_{\text{exp}} \) [W] |
| Previous structure in ref.[33] | Measured | \( 6.5 \times 10^{-11} \) | \( 1 \times 10^3 \) | \( 4.225 \times 10^{-18} \) |
| | Optimized | \( 2.2 \times 10^{-11} \) | \( 21 \times 10^6 \) | \( 1.016 \times 10^{-14} \) |
| This structure for 3.8 μm-gap | Measured | \( 2.3 \times 10^{-9} \) | \( 1 \times 10^3 \) | \( 5.290 \times 10^{-15} \) |
| | Optimized (Estimated) | \( 1.15 \times 10^{-7} \) | \( 21 \times 10^6 \) | \( 2.777 \times 10^{-11} \) |

| Table 4 | Calculated maximum possible output. |
|---------|----------------------------------|
| f [Hz] | a [m/s²] | \( Y_0 \) [m] | Z_o [m] | \( P_{\text{max}} \) [W] |
| Previous structure in ref.[33] | 1,154 | 1 | \( 1.904 \times 10^{-8} \) | \( 3 \times 10^{-5} \) | \( 4.131 \times 10^{-8} \) |
| This structure for 3.8 μm-gap | 1,430 | 6 | \( 7.440 \times 10^{-8} \) | \( 3 \times 10^{-5} \) | \( 3.071 \times 10^{-7} \) |
and smaller $S(f, R_L)$ means better structure.

By using Eq. (9) into Eq. (12), $S(f, R_L)$ is expressed as

$$S(f, R_L) = \left| \frac{\sigma}{R_L T} \right|$$  \hspace{1cm} (14)

The ratio of $S(f, R_L)$ of present/previous $= |\sigma_{\text{present}} / \sigma_{\text{previous}}| / (I_{\text{present}} / I_{\text{previous}}) = |20.7 \times 10^{-9} / -3.5 \times 10^{-9}| / (1.15 \times 10^{-9} / 2.2 \times 10^{-11}) = 1/8.83 = 0.11$. This means that the structure of the present device is 8.83 times better performance to power output than that the previous one.

From the value of two indices, we can say that the present device is 367 times more effective than the previous one, and contribution of the structure itself to the effectiveness is 8.83 times better. It was demonstrated experimentally that narrowing the gap boosts the current, indicating that this technique is effective for improving the current for small sized energy conversion. These results indicate significant progress as regards miniaturized MEMS energy harvesters for wireless sensor nodes in future ubiquitous networks.

5. Summary

A MEMS electrostatic energy harvester with a slit-and-slider structure for a micron level gap was fabricated by using thick-multilevel interconnection technology. Nested flip-chip assembly was applied to narrow the gap between the slit and slider chips. The fabricated device resonated with the expected frequency induced by an external mechanical vibration. The energy harvester equipped with a conventional electret made of ETFE film generated a 2.3 kHz. In order to reveal the effect of a parasitic capacitance, an equivalence circuit model was introduced. The derivations from the model show that the parasitic capacitance is negligible for this low impedance current measurement by a lock-in amplifier. In order to compare the present device with our previous device for the power output, the harveser effectiveness and structural normalized parameter are introduced. The values of the effectiveness improved by 367, and the contribution of the structure itself to the effectiveness is 8.83 times larger than the previous one.

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