Computer Simulation of the Response of a Semiconductor Wafer with a Self-Affine Pattern in the Form of a System of Coupled Ring Grooves to Electromagnetic Radiation

以「耦合環形溝槽系統」形式呈現自相似圖案之半導體晶圓對電磁輻射反應的電腦模擬

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Abstract **摘要**

We simulated the response of a surface with a circular relief on a semiconductor wafer constructed using self-affine transformations to the effect of an incident electromagnetic wave. The study assumed that the main mechanism leading to the reaction of the plate to incident radiation is electric polarization, which, for example, is the basis for the functioning of a number of electronic components, such as a MOS FET or a CCD. Since silicon belongs to polarizable materials, a spatial separation of charges occurs in a changing electric field in the volume of a silicon crystal in accordance with the law of change of field. If a silicon wafer is used, on one of the surfaces of which a certain relief is created, then the distribution of charges under the relief will be uneven in space in accordance with the pattern of this relief.

我們模擬了以自相似變換構成、表面帶有圓形微觀地形的半導體晶圓在入射電磁波作用下的反應。研究假設使晶片對入射輻射產生反應的主要機制為電極化，例如這正是許多電子元件（如 MOS FET 或 CCD）運作的基礎。由於矽屬於可極化材料，在變化的電場中，矽晶體體積內會依照場的變化規律產生電荷的空間分離。若在矽晶圓的一側表面加工出特定的微觀地形，則該地形下方的電荷分佈將會依照此地形的圖案在空間上呈現不均勻分布。

Keywords Regular self-affine microrelief • Ring-shaped grooves • Electric field • Computer simulation . Wave structure

關鍵詞 規則自仿微觀輪廓 • 環狀溝槽 • 電場 • 電腦模擬 . 波狀結構

1 Introduction **1 介紹**

Regular microrelief surfaces have been used for a long time. These include, for example, diffraction gratings. Widely used are devices on surfactants, the basis of which is also a regular surface relief. Now there is a study of new areas of application of devices with a regular microrelief on the surface. For example, there are studies [1] where the effect of thermal radiation from such heated surfaces is investigated. It was shown [1] that in the near field this radiation has spatial coherence.

規則微觀輪廓表面已被長期使用。其中包括例如繞射光柵。廣泛使用的還有基於表面活性劑之上的裝置，其基礎也是規則的表面形貌。現在有人在研究具有規則微觀輪廓表面的裝置的新應用領域。例如，有研究[1]探討了此類受熱表面的熱輻射效應。文獻[1]顯示，在近場下這種輻射具有空間相干性。

In our study, we present an object that also has the properties of self-similarity and scale invariance, but so far it is not widely represented in the studies. It is obtained in the process of scaling and rotation of the circle taken as a basis and further transformations of the aggregates thus obtained [2].

在我們的研究中，我們提出了一種同樣具有自相似性和尺度不變性質的對象，但迄今在研究中尚未被廣泛呈現。它是在以圓形為基礎進行縮放與旋轉，並對由此得到的聚合體進一步變換的過程中得到的[2]。

An affine transformation of a vector whose origin coincides with the origin and the end has coordinates (x_1, y_1), into a vector whose origin is at a point with coordinates (b_1, b_2), and the end at a point with coordinates (x_2, y_2) has the form [3]:

一個原點與原點重合且端點座標為 (x_1, y_1) 的向量，經仿射變換為一個原點位於座標 (b_1, b_2)、端點位於座標 (x_2, y_2) 的向量，其形式為 [3]：

$$\begin{cases} x_2 = a_{11}x_1 + a_{12}y_1 + b_1 \\ y_2 = a_{21}x_1 + a_{22}y_1 + b_2 \end{cases}$$

ISystem (1) can be represented in the form of the matrix:

ISystem (1) 可以表示為矩陣的形式：

$$\begin{bmatrix} x_2 \\ y_2 \end{bmatrix} = \begin{bmatrix} a_{11} & a_{12} & b_1 \\ a_{21} & a_{22} & b_2 \end{bmatrix} \begin{bmatrix} x_1 \\ y_1 \\ 1 \end{bmatrix}$$

and to illustrate by Fig. 1.

並可由圖 1 說明。

Also, using affine transformations, you can assign the operation of rotation through the angle α.

此外，利用仿射變換，也可以指定以角度 α 進行旋轉的操作。

$$T_1 = \begin{bmatrix} \cos\alpha & -\sin\alpha & 0 \\ \sin\alpha & \cos\alpha & 0 \end{bmatrix}$$

and scaling. **以及縮放。**

$$T_2 = \begin{bmatrix} m & 0 & 0 \\ 0 & m & 0 \end{bmatrix}$$

For $m > 1$, the distance from the origin occurs; for $m < 1$, it approaches the origin.

對於 $m > 1$ ，距離原點會增加；對於 $m < 1$ ，則會接近原點。

With an increase or decrease in the scale of the figure by a factor of m, an increase or decrease in its size by a factor of m occurs.

當圖形的尺度改變 m 倍時，其尺寸會相應改變 m 倍（放大或縮小）。

Figure 1: Fig. 1 Affine transformations of the vector

圖 1：圖 1 向量的仿射變換

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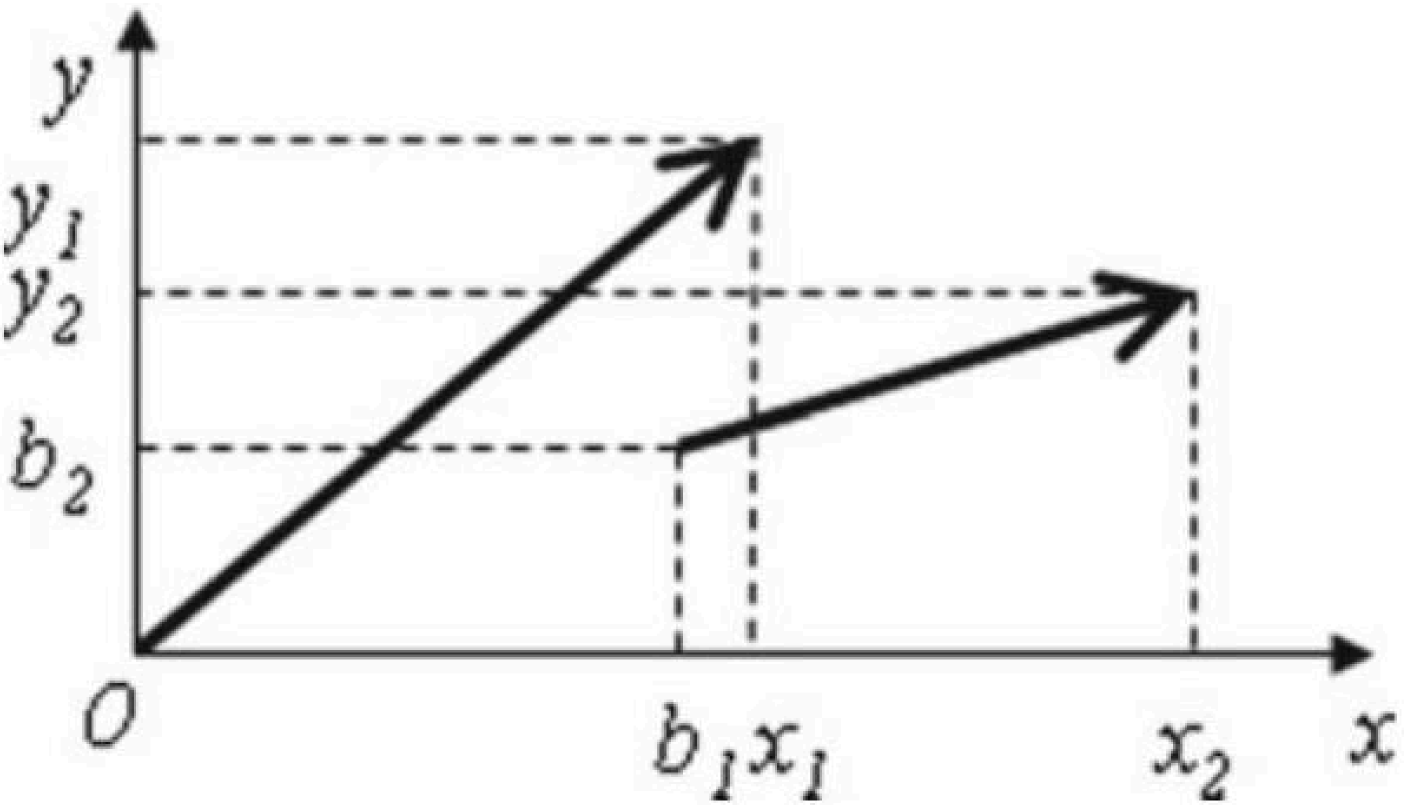

Figure 2: Fig. 2 The LIFETUNE resonator

圖 2：Fig. 2 LIFETUNE 共振器

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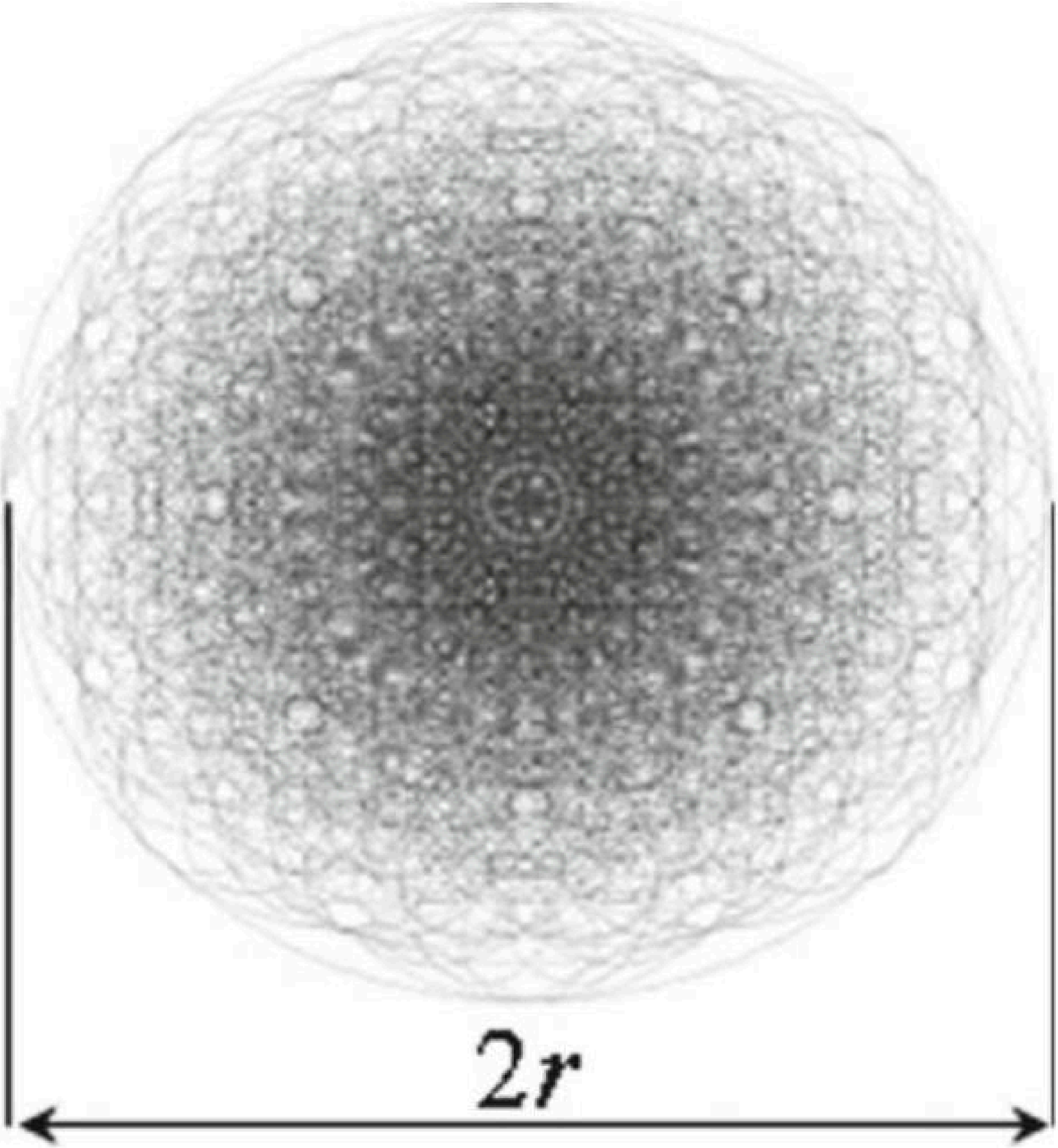


2 Object of Study

2 研究對象

The behavior of a silicon wafer was studied, on the surface of which a pattern of a large number of ring-shaped grooves was etched by plasma-chemical etching (see Fig. 2). The studied object, the LIFETUNE resonator, is a silicon wafer on the surface of which there are annular grooves 0.2μ m wide and 0.8μ m deep, the pattern of which obeys the laws of self-similarity and scale invariance, and is based on affine transformations that is, this surface is self-affine by construction [2].

研究了矽晶圓的行為，其表面經等離子化學蝕刻刻劃出大量環形溝槽的圖樣（見圖 2）。所研究的物件 LIFETUNE 共振器，是一塊矽晶圓，表面具有寬為 0.2μ m 、深為 0.8μ m 的環形溝槽，該圖樣遵循自相似與尺度不變的規律，並以仿射變換為基礎——也就是說，該表面在構造上是自仿射的 [2]。

This figure was obtained as a result of the implementation of affine transformations, the initial stages of which are illustrated in Fig. 3.

此圖為實施仿射變換的結果，初始階段如圖 3 所示。

3 Experiment 3 實驗

We considered the interaction of an electromagnetic wave with a plate surface for a non-stationary case, for a two-dimensional model. A change in the distribution of tension with time over the surface of the resonator was simulated for various boundary conditions.

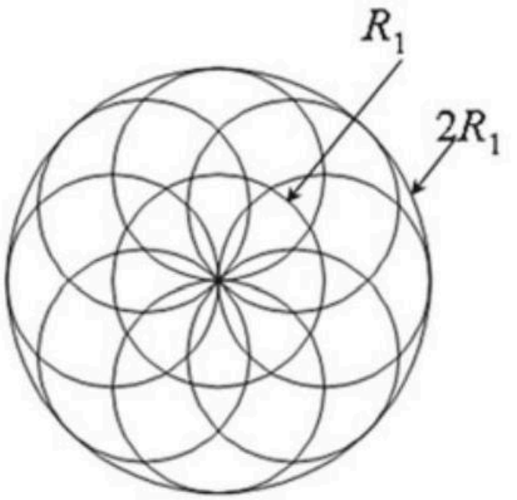
我們考慮了電磁波與板材表面在非靜態情況下的相互作用，採用二維模型。針對不同邊界條件，模擬了共振器表面張力隨時間變化的分佈。

An electric field interacting with a semiconductor causes a charge displacement phenomenon and, due to the fact that the plate has a smaller thickness in the “groove” region, the concentration of charge carriers in the groove region will be higher than in neighboring regions. Then most of the charge carriers are concentrated in the regions under the grooves (see Fig. 4).

電場與半導體相互作用會引起電荷位移現象，而且由於在「溝槽」區域薄片厚度較小，溝槽區的載子濃度會比鄰近區域高。因此大多數載子會集中在溝槽下方的區域（見圖 4）。

Let the charge density of two adjacent grooves be q_1 and q_2, respectively, and the potentials φ_1 and φ_2 (see Fig. 5).

設兩相鄰溝槽的電荷密度分別為 q_1 和 q_2 ，對應的電位為 φ_1 和 φ_2 （見圖 5）。



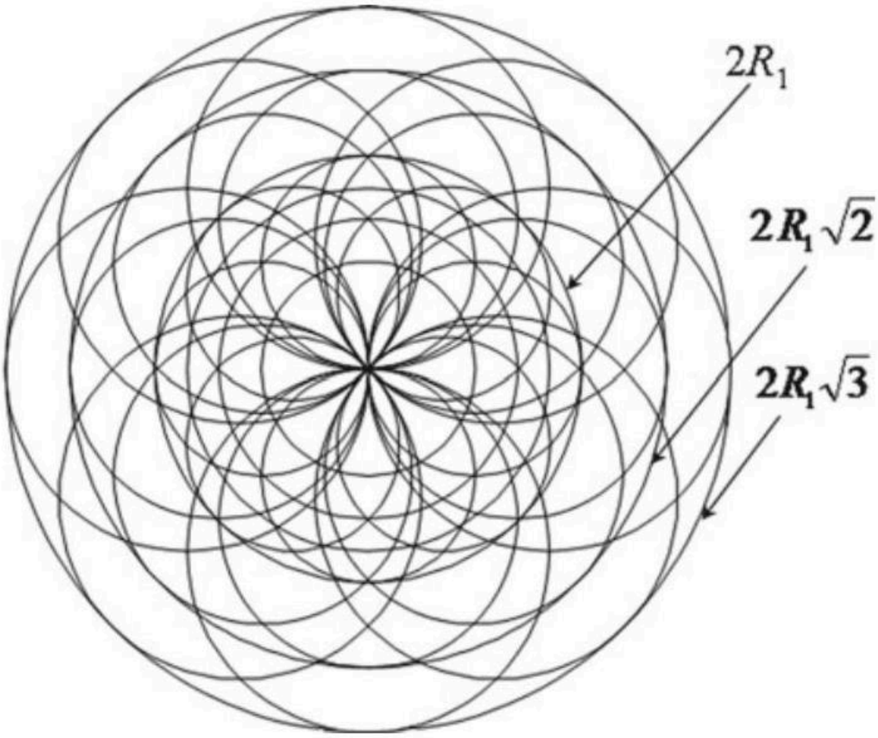


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Figure 3: Fig. 3 Create a self-affine relief

Figure 4: Fig. 4 The charges

圖 4：圖 4 電荷分佈

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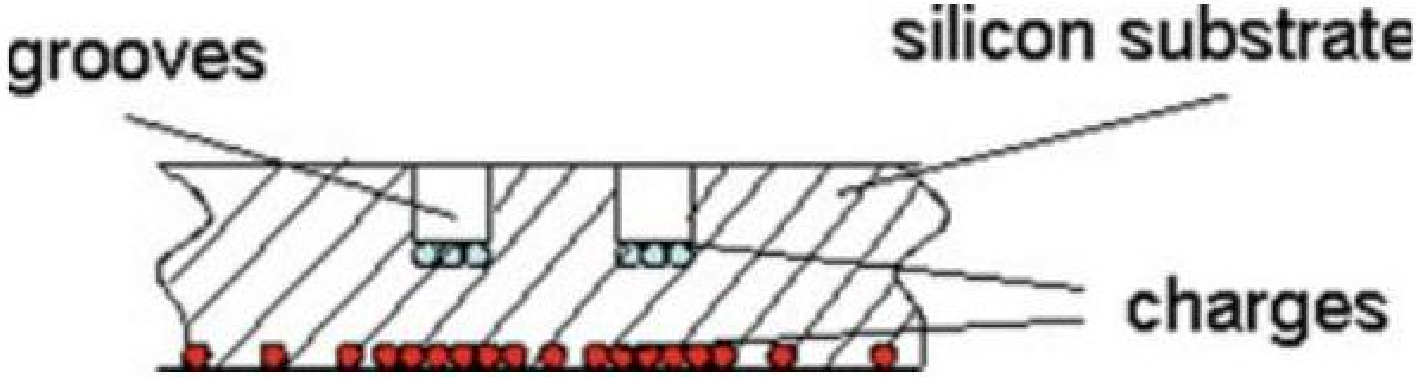

Figure 5: Fig. 5 The potentials φ_1 and φ_2

圖 5：圖 5 電勢 φ_1 與 φ_2

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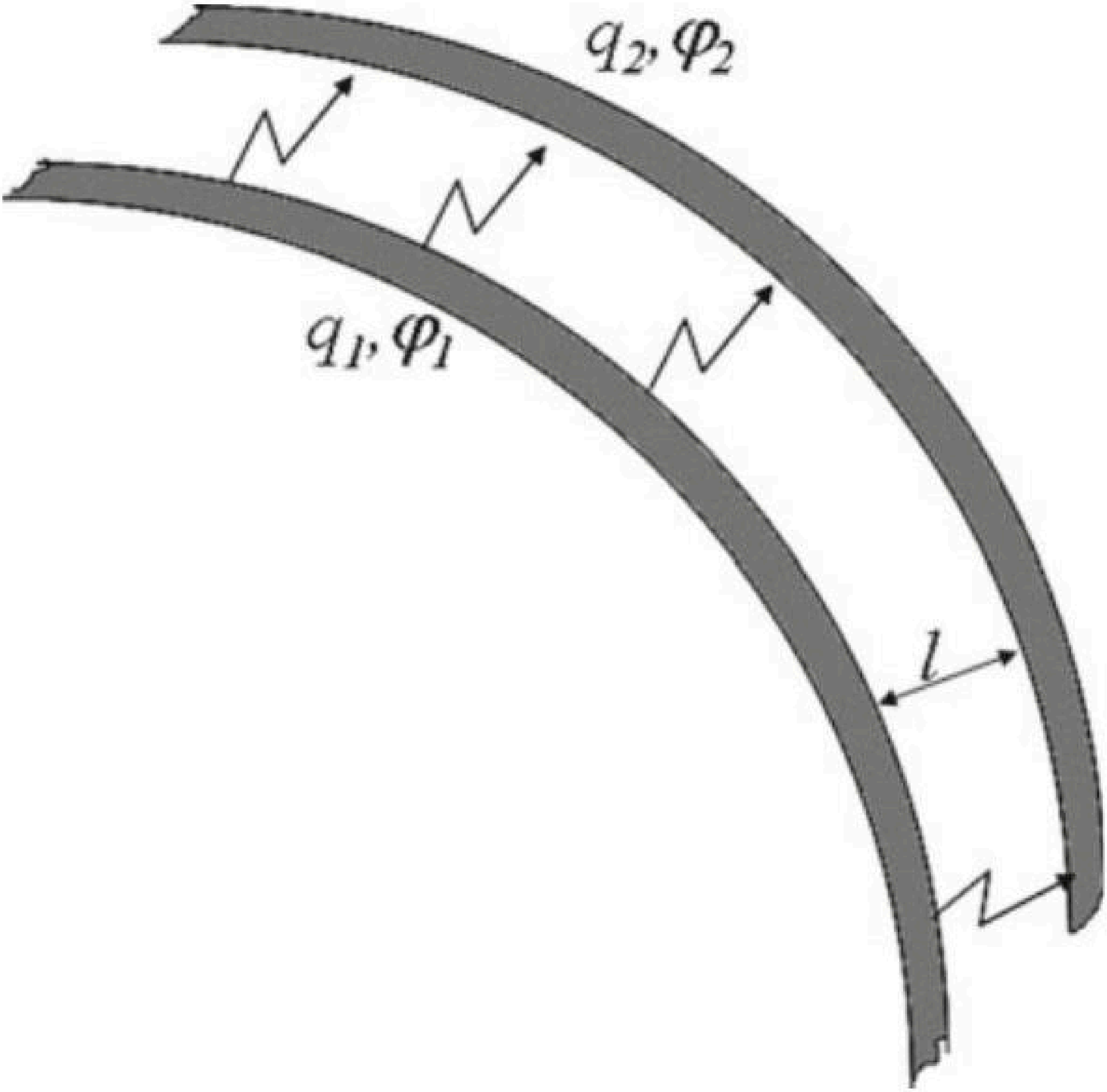

When the potential reaches some critical value φ_c, a current arises along the shortest distance between the grooves. The induced electric field strength E_{ind} then has the form $E_{\text{ind}} = (\varphi_1 - \varphi_2)/l$.

當電位達到某個臨界值 φ_c 時，沿著溝槽之間最短距離會產生電流。誘發的電場強度 E_{ind} 隨後具有形式 $E_{\text{ind}} = (\varphi_1 - \varphi_2)/l$ 。

The mathematical model for this case has the form:

在此情況下的數學模型具有如下形式：

Figure 6: Fig. 6 The distribution of $E\ (x, y)$ over resonator in plane (x, y)

圖 6：圖 6 在平面 (x, y) 共振器上 $E\ (x, y)$ 的分佈

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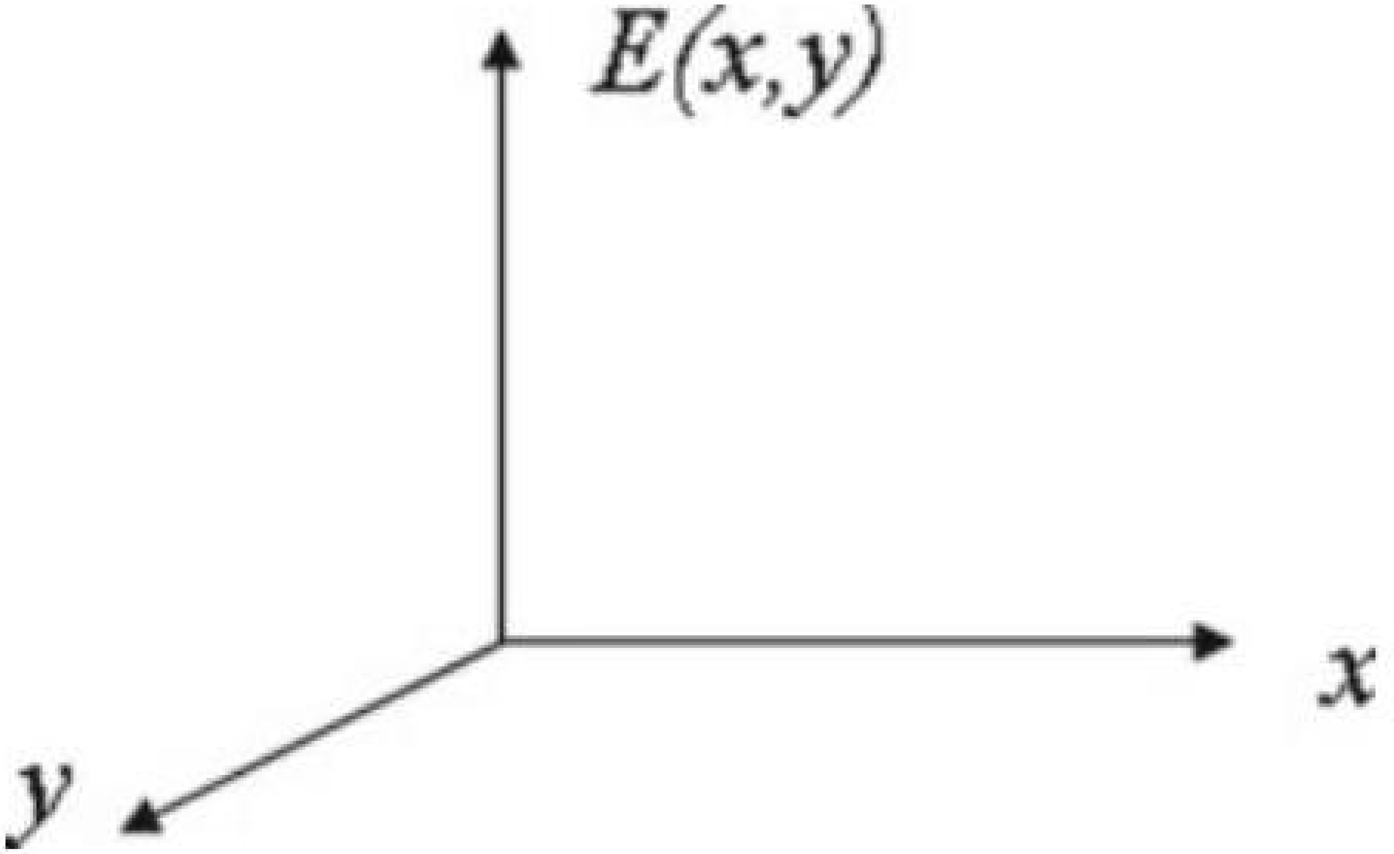


$$\frac{\partial E}{\partial t} = \alpha_1 \left(\frac{\partial^2 E}{\partial x^2} + \frac{\partial^2 E}{\partial y^2} \right) - \frac{E}{\alpha_2}.$$

where: E-electric field strength, t-time; α_1, α_2 are the coefficients, x, y are the coordinates. In the simulation, it was assumed that the law of current change when the potential reaches the value $i = 1 - \left(e^{-\beta t} \cos\left(\omega_0 t\right)\right)$.

其中： E — 電場強度， t — 時間； α_1, α_2 為係數， x, y 為坐標。模擬中假定當電位達到值 $i = 1 - \left(e^{-\beta t} \cos\left(\omega_0 t\right)\right)$ 時電流變化遵循的規律。

The condition at the cavity boundary: $E = 0$ for $r > \sqrt{x^2 + y^2}$. In the last expression, r is the radius of the resonator (Fig. 2). In addition, the results were compared with the sink in the center of the cavity $(E = 0)$ and without it, when the value of E in the center is obtained as a result of calculation by model (5).

腔體邊界處的條件： $E = 0$ 對於 $r > \sqrt{x^2 + y^2}$ 。在最後一個表達式中， r 為諧振腔的半徑（圖 2）。此外，結果還與腔體中心存在耗散器 $(E = 0)$ 與不存在耗散器的情況進行了比較——當中心的值 E 為由模型（5）計算得到的結果時。

4 Results and Discussion

4 結果與討論

The simulation results in the form of the distribution of the value of $E(x,y)$ (see Fig. 6) are shown in Fig. 7. Since model (5) is dynamic, the figures show different stages of the process at different times, in which waves of different lengths and orientations are visible.

以 $E(x,y)$ 值分佈形式的模擬結果（見圖 6）如圖 7 所示。由於模型（5）是動態的，圖中展示了不同時間下過程的不同階段，其中可見不同波長與方向的波動。

The sizes of the plate along the x and y axes are 20×20 mm. Waves with different lengths and orientations arise due to the complex structure of the resonator surface, which creates an “orchestra” of interconnected wave processes.

板沿著 x 與 y 軸的尺寸為 $20 \times 20\ \mathrm{mm}$ 。由於諧振腔表面的複雜結構，產生了不同波長和方向的波，形成了相互連結的波動過程的「交響樂」。

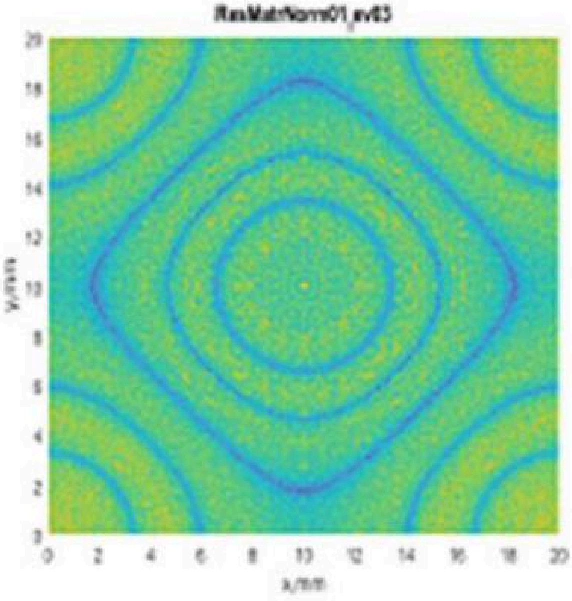
5 Conclusions 5 結論

Regardless of the conditions at the surface boundary, after some time t_{s}, a stable multi-frequency distribution of the electric field strength over the resonator surface is established.

不論表面邊界的條件如何，經過一段時間 t_{s} 後，諧振腔表面上電場強度會建立起穩定的多頻分佈。

The surface under consideration acts as a transducer of the radiation incident on it and gives a response in the form of a set of waves. When the period of incident electromagnetic radiation changes, the distribution of the electric field on the surface retains its character.

所考慮的表面充當入射輻射的能量轉換器，以一組波的形式給出響應。當入射電磁輻射的週期改變時，表面上電場的分佈保持其特性。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y, mm
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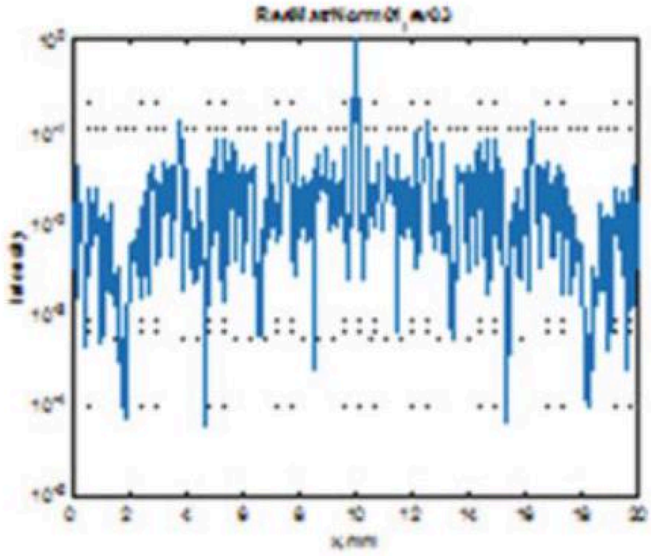
0 2 4 6 8 10 12 14 16 18 20


ResMatrNorm01_ev03
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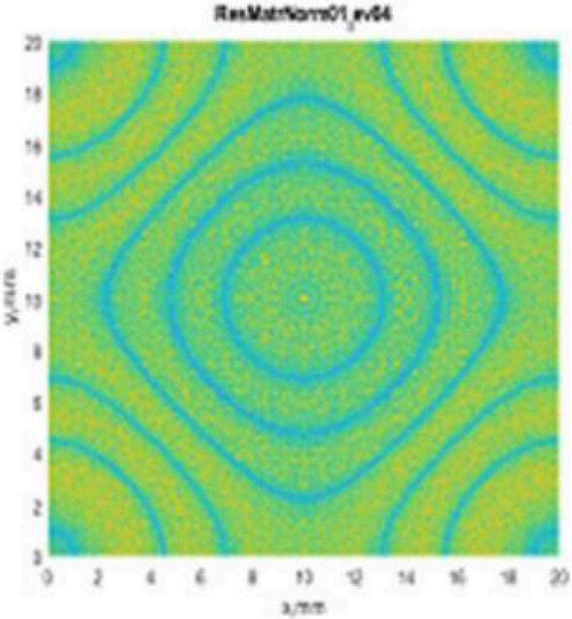
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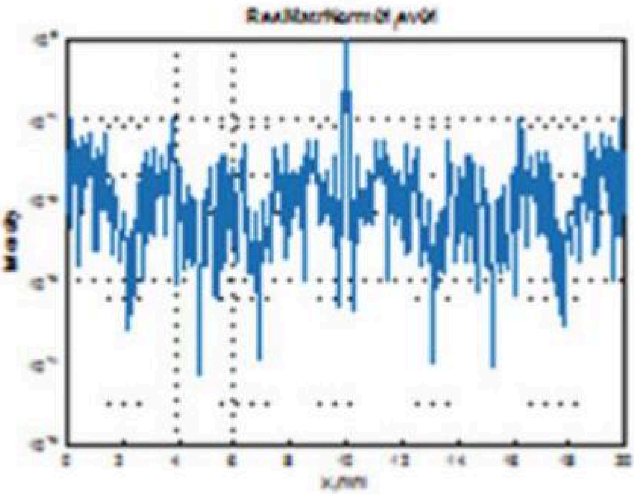
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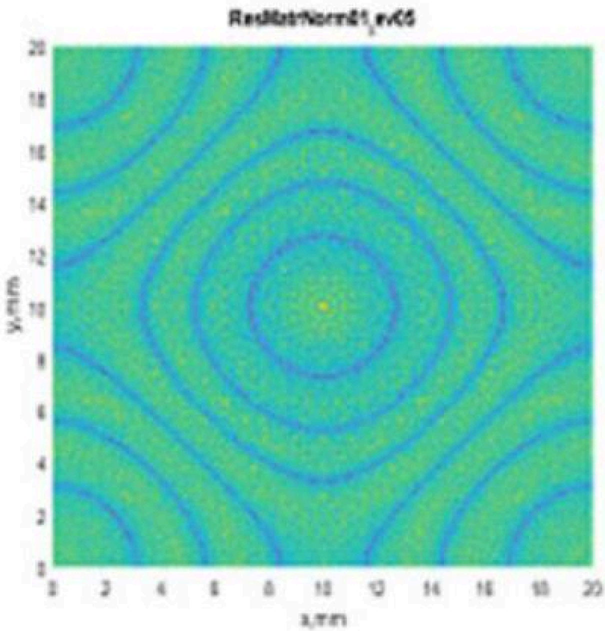
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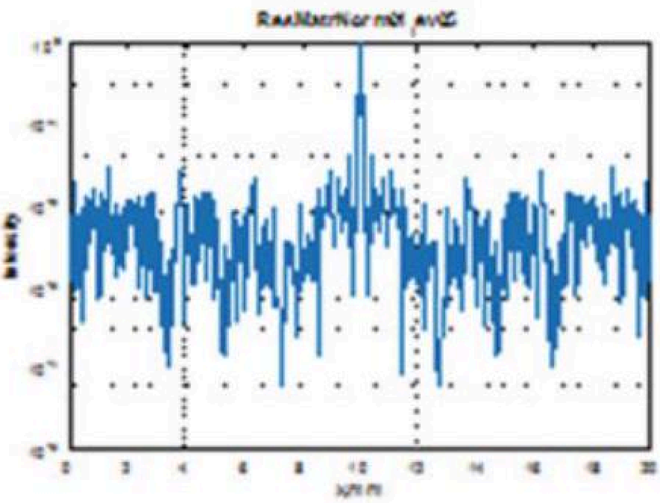
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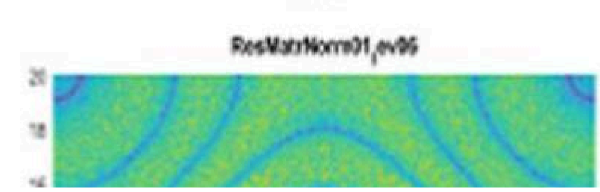
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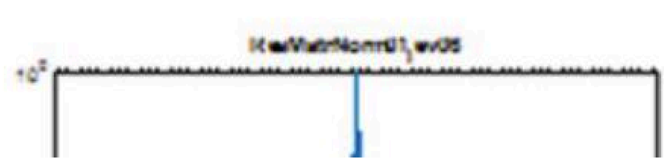
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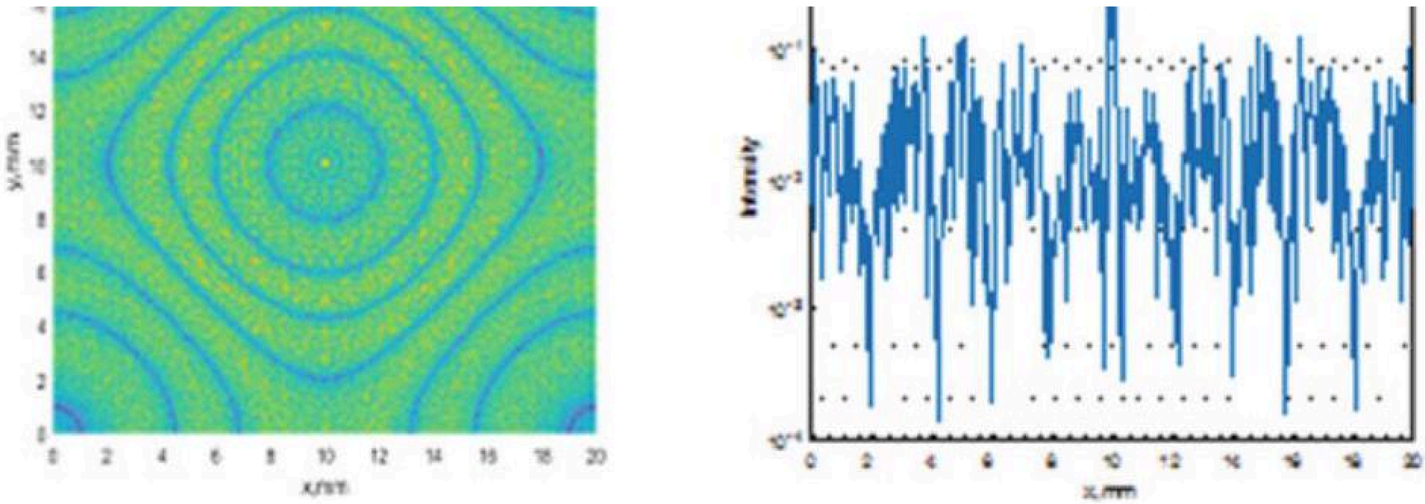

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Figure 7: Fig. $7E(x, y)$. Change over time

圖 7：圖 $7E(x, y)$ 。隨時間的變化

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