Electronic Supplementary Material (ESI) for Nanoscale.

Supporting Information for

Dual Chaos Encryption for Color Image Enabled in a WGM-Random Hybrid Microcavity

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1. Materials and Device Preparation

Solution preparation: Firstly, 3 mg Rh6G was dissolved into 1 mL Dichloromethane (DCM) with the amount of Ag NPs at 0.5 ~ 4×10^{-2} mg or TiO_2 NPs at 0.04 mg, respectively, obtaining the solution with different scattering distribution. Then, epoxy resin (n=1.5) and PMMA were added, with the mass of 163.8 mg. After that, the mixture was sealed and stirred at room temperature for 2 hours. Finally, let the mixture stand for 30 minutes to remove bubbles and obtain a uniform solution mixture.

Device preparation: The metal needle of the syringe is about 3 cm away from the roller. The positive high voltage loaded on the needle and the negative high voltage loaded on the roller are 4.5 kV. The translation speed of the syringe is 2 cm/s, and the rotation speed of the roller is controlled at 30 rpm.

2. Material Absorption Analysis

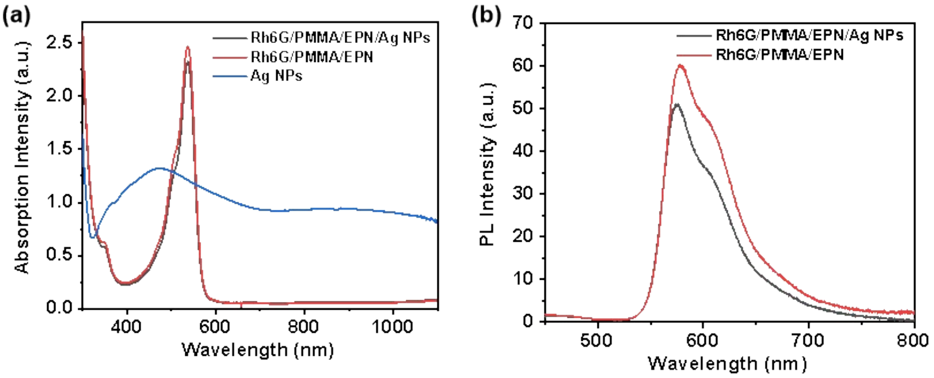

Figure S1. The absorption and emission spectrum of PMMA/EPN/Rh6G blend films with or without Ag NPs and the absorption of Ag NP dispersion.

Material absorption needs to consider the absorption of pump light energy and excited light energy. According to the absorption formula:

$$I = I_0 e^{-\alpha z} \tag{1}$$

where I is the transmitted light intensity, I_0 is the incident light intensity, α is the absorption coefficient of the material and z is the absorption length.

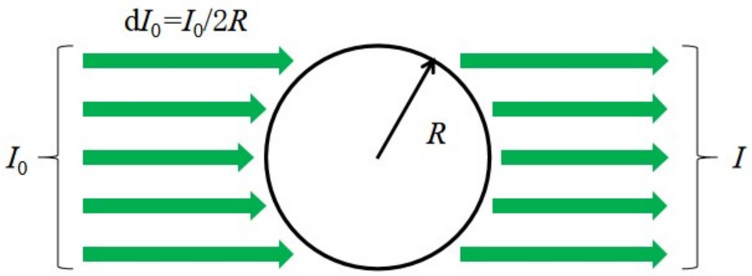

Figure S2. Material absorption model of pump light

As shown in Figure S2, assuming that the energy distribution of the pump light is uniform, the total energy of the pump light irradiated on the fiber is I_0, the cross section of the fiber is a disk, the absorption coefficient of each point on it is uniform, and the radius of the disk is r, then the integration of the disk can be obtained:

$$I = \int_{-R}^{R} \frac{I_0}{2R} e^{-2\alpha\sqrt{R^2-x^2}} \mathrm{d}x \tag{2}$$

after simplification, the following results are obtained:

$$I = I_0 (1 - 2\alpha R \int_0^1 \sqrt{1-x^2}\, e^{-2\alpha R x} \mathrm{d}x) \tag{3}$$

where I is the total outgoing light intensity, I_0 is the total incident pump light intensity, α is the absorption coefficient of the material to the pump light, and the difference between the two intensities is the absorbed part. After simulation with MATLAB, it is found that the *I* value will decrease sharply with the increase of diameter *R*, and finally tend to 0, which means that the material absorption will increase sharply with the increase of fiber diameter.

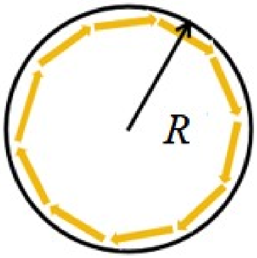

Figure S3. Material absorption model of excited light.

Then, the absorption of excited light energy is considered, and the material absorption model is shown in Figure S3. The excited light circulates continuously in the WGM cavity. According to the absorption formula (1), the initial excitation light intensity is set as I_0', and the absorption coefficient of the material to the excited light is α'. If the number of cycles is n, then after n cycles, the transmitted excitation light intensity I' is

$$I' = I_0' e^{-\alpha' \cdot \mathrm{n} \cdot 2\pi R} \tag{4}$$

The sum of the absorption of pump light and excited light is the total absorption of the material. The above is the material absorption of WGM laser. For random laser, just replace $2\pi R$ in equation (4) with the optical path length of random laser.

3. Specific Encryption Steps

3.1 WGM-random hybrid cavity laser coding

The WGM-random hybrid cavity laser coding is shown in Step1 of Figure 5, of which, WGM laser can be encoded by FSR or peak position, while random laser can be encoded by peak position or coherence length. In order to meet the control conditions of $0<X_0<1$ and $3.569<u<4$, we take a certain proportion (k) of the sum value of each peak position from the random laser (unit: μm) as the initial parameter X_0 for 1D logistic system; and adopt a certain proportion (i) of the FSR value of the WGM laser (unit: nm) as the control parameter u. Herein, according to the obtained random laser and WGM laser spectrum in a hybrid cavity, we take k=10 and i =0.3 as the control coefficient and then obtain that these two initial values of X_0 and u are 0.5 and 3.6, respectively.

3.2 Generation of chaotic sequence via dual chaotic system

Following, the initial values of $X_0=0.5$ and $u=3.6$ are plugged into the Logistic chaotic system, according to the formula 2 and proceed p iterations to obtain a chaotic array $\{X_{1,} X_2, \cdots\cdots X_p\}$. Of these, the M_{th} and N_{th} values in the above sequence are intercepted as the initial values Y_0 and Z_0 of 2D Henon system. The output value of the 2D Henon chaotic system is the Y_q and Z_q sequences composed of q numbers and q is the number of iterations. One of them is selected as the encryption sequence, such as Y_q, $\{Y_0, Y_1, \cdots\cdots Y_q\}$. Finally, M×N numbers are obtained from this sequence and thus, the chaotic sequence $L_{M\times N}$ generated by the dual chaotic system, $\{Y_{M,} Y_{M+1}, \cdots\cdots Y_{M+M\times N-1}\}$, which is defined as the chaotic sequence table. Then the sequence is arranged into a M×N matrix, in which, its elements are sorted according to the rules from small to large. The index of the elements at each position after sorting in the original chaotic sequence table is recorded as the encryption table. Owing to the diversity and randomness of random lasers, so as the obtained encryption tables for image encryption. At this point, a chaotic sequence via the dual chaotic system is built, named as Step2.

3.3 Scrambling encryption

Here, we take a 2×3 pixel image as an example, the green encryption table is obtained by sorting the green chaotic sequence table obtained via proceeding Step1 and Step2. In this image, each pixel is represented by a color. Rearrange each pixel of the image, according to the position recorded in the encryption table in Step2, so as to scramble the position of the original image and generate a disordered encrypted image.

Decryption relies on the previously generated encryption table. Sort the elements in the encryption table from small to large, record the index of the elements at each position in the encryption table, and record it as the decryption table. Shift the encrypted image according to the position of the decryption table, and the final decrypted image can be obtained, as shown in Step3 of Figure 5. That is, each color block corresponds to a number and a serial number at the same time, for example, the red color block corresponds to the number 4 and serial number ① at the same time. The sequence of the serial number is the encryption table, and the sequence of the number is the decryption table.