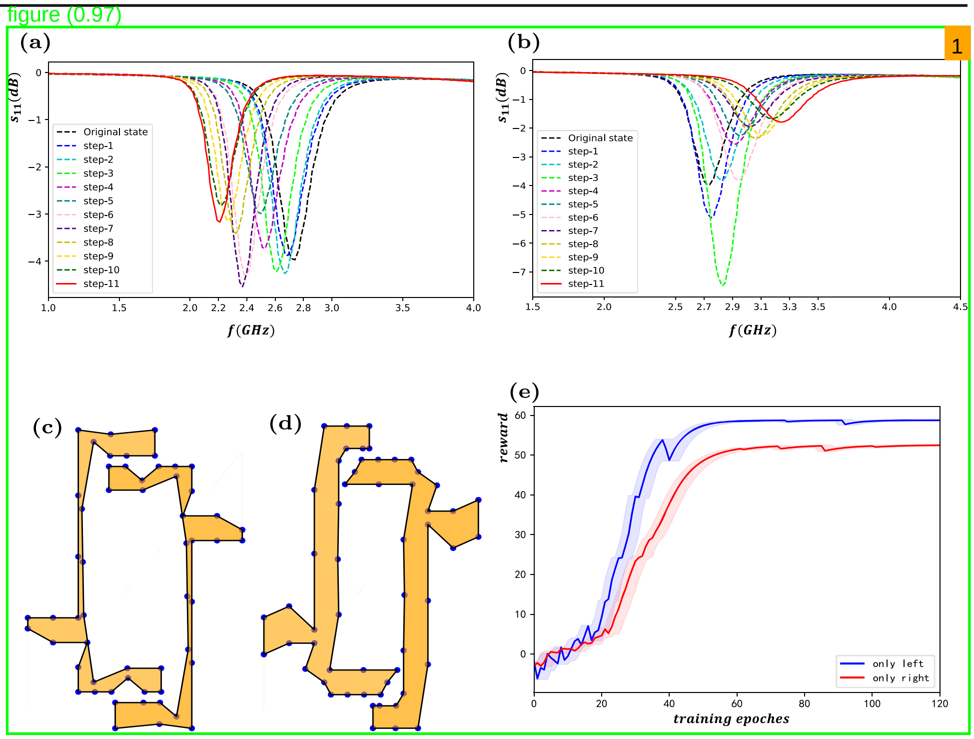

Fig. 9 Stepwise training method. **a,** Training results of the centre frequency with a leftwards shift. **b,** Training results of the centre frequency with a rightwards shift. **c,** Circuit grid parameter matrix for Step 11 in Fig. 9a. **d,** Circuit grid parameter matrix for Step 11 in Fig. 9b. **e,** Training curve

The aim of the PAAC-K model in this example is to optimize the hairpin filter according to different tasks. The initial parameters of the hairpin structure are set randomly and regularly, and the performance is far from that of the standard. The hairpin structure initial parameters are shown in Fig. 7 and Table 1.

According to microstrip filter theory [49], the performance of the hairpin filter depends mainly on the size of different physical parameters, including the length, distance between resonators, hairpin arm length, hairpin resonator line width, distance between the double arms of a single resonator and tap position. The disadvantage of the traditional method is that changing the physical parameters indirectly affects the electromagnetic performance. In contrast, the method in this paper uses a clustering algorithm to extract characteristics directly, thus changing the grid matrix based on request. The filter shape mesh is divided for clustering different actions. The agent changes the grid matrix for the design with the neural network model, which establishes the relationships in the circuit grid parameter matrix of the different frequencies. Thus, the relationship of the structure is obtained, and the automatic design of the irregular filter is realized.

We have designed four task examples of hairpin filters with different bandpass frequencies, as shown in Table 2. All work is performed by the agent. The designed centre frequencies are 2.75 GHz, 3.15 GHz, 2.4 GHz, and 2.15 GHz, and the filter size is limited between sub_x and sub_y. All parameter settings are based on the design standards.

4.3 Results and discussion

A visualization of the clustering results is shown in Fig. 5. PAAC-K extracts 4 categories. Increasing the coupling ratio causes a downwards shift of the S_{11} curve (Fig. 8a and e), decreasing the resonant frequency causes a leftwards shift of the S_{11} curve (Fig. 8b and f), and increasing the resonant frequency causes a rightwards shift of the S_{11} curve (Fig. 8c and g).

From the filter design view, the "cluster centre 4" category (Fig. 5) of the filter performance is further away from the target. To achieve better S_{11} performance, underperforming operations are excluded from the typical action cluster.

The number of iteration steps set for training is 11 (Fig. 9), indicating that agents can convert the matrix up to 11 times during training. The centre frequency from 2.70 GHz to 2.2 GHz is achieved by shortening the resonator width and that from 2.70 GHz to 3.2 GHz is achieved by expanding the resonator width. When designing a filter for a task, the agent selects the initial state using the stepwise training method that is closest to the target frequency. See Section 3.3.3 for more information.

In Task 1, the target centre frequency is 2.75 GHz, and the passband frequency is from 2.6 GHz to 2.9 GHz. The filter's original state (centre frequency of 2.70 GHz) is shown in Fig. 7. The agent has learned to gradually adjust the coupling coefficient between resonators to reduce the reflection loss of the filter to complete the circuit design. As shown in Fig. 10 a-c, the task objectives are achieved quickly.