

High-capacity and robust information transmission using generalized random structured beams and deep learning–based decoding: Supplementary Information

Yun Liu,[†] Xinlei Zhu,[†] Jidong Wu,[†] Shuqin Lin,[†] Min Li,[‡] Xiaofeng Peng,[†]
Yangjian Cai,^{*,†} and Jiayi Yu^{*,†}

[†]*Shandong Provincial Key Laboratory of Light Field Manipulation Physics and Applications & School of Physics and Optoelectronics, Shandong Normal University, Jinan 250014, China*

[‡]*Shandong Beifang Optical Electronics Co., Ltd., Taian 271000, China*

E-mail: yangjian_cai@163.com; jiayiyu0528@sdu.edu.cn

Abstract

This Supplementary Information provides additional technical details supporting the article “High-capacity and robust information transmission using generalized random structured beams and deep learning-based decoding.” It presents the mapping strategy between grayscale values and random modes, describes the complex amplitude modulation encoding algorithm, and the key parameters of the convolutional neural network used in this study.

Supplementary Note 1: Mapping relationship

In Figs. S1–S10, we present the mapping relationships among grayscale values, beam parameter sets $(n, l, \delta_x, \delta_y)$, and the corresponding simulated intensity distributions of the random modes.

Supplementary Note 2: Complex amplitude modulation encoding algorithm

As shown in the main text, the cross-spectral density of a random structured beam can be expressed as $W(\mathbf{r}_1, \mathbf{r}_2) = \tau^*(\mathbf{r}_1) \tau(\mathbf{r}_2) \langle T^*(\mathbf{r}_1) T(\mathbf{r}_2) \rangle$. When $T(\mathbf{r})$ satisfies the zero-mean Gaussian random statistical property and has a sufficient number of realizations, the cross-spectral density can be expressed as $W(\mathbf{r}_1, \mathbf{r}_2) = \sum_{n'}^N \alpha_{n'} U_{n'}^*(\mathbf{r}_1) U_{n'}(\mathbf{r}_2)$, where N is the number of modes, $\alpha_{n'} = 1/N$ is the mode weight, and $U_{n'}(\mathbf{r})$ represents the complex random mode. Therefore, by designing a complex random transmission function, a random structured beam with predetermined characteristics can be obtained.

In this study, we express the complex random transmission function as

$$T_m(\mathbf{r}) = \int R(\mathbf{v}) \sqrt{p_m(\mathbf{v})} H(\mathbf{r}, \mathbf{v}) d^2\mathbf{v}, \quad (\text{S1})$$

where $p_m(\mathbf{v})$ is an element of the power spectral density function set $\{p_m(\mathbf{v})\}_M$, $H(\mathbf{r}, \mathbf{v}) = \tau(\mathbf{r}) \exp(ik\mathbf{v} \cdot \mathbf{r})$ is the response function, and $R(\mathbf{v}) = a(\mathbf{v}) + ib(\mathbf{v})$, where $a(\mathbf{v})$ and $b(\mathbf{v})$ are two sets of Gaussian random variables with unit variance and zero mean. This allows us to obtain the complex amplitude random mode $T_m(\mathbf{r})$.

Supplementary Note 3: Parameters of the convolutional neural network

Model training was performed using the Adam optimizer, which adaptively adjusts the learning rate based on first- and second-order gradient moments. A relatively large learning rate was used at the initial stage to accelerate convergence, followed by gradual reduction for fine refinement. The batch size was set to 128, and the network was trained for 80 epochs. The initial learning rate was set to 0.0001 and was reduced by a factor of 10 at epochs 60 and 70, respectively.

Table S1: VGG-16 Net Model Details

Layer		Kernel Size	Stride	Padding	Output Size	Channels
Input	–	–	–	–	224×224	3
Block 1	Conv2d+ReLU	3×3	1	1	224×224	64
	Conv2d+ReLU	3×3	1	1	224×224	64
	Maxpool	2×2	2	0	112×112	64
Block 2	Conv2d+ReLU	3×3	1	1	112×112	128
	Conv2d+ReLU	3×3	1	1	112×112	128
	Maxpool	2×2	2	0	56×56	128
Block 3	Conv2d+ReLU	3×3	1	1	56×56	256
	Conv2d+ReLU	3×3	1	1	56×56	256
	Conv2d+ReLU	3×3	1	1	56×56	256
	Maxpool	2×2	2	0	28×28	256
Block 4	Conv2d+ReLU	3×3	1	1	28×28	512
	Conv2d+ReLU	3×3	1	1	28×28	512
	Conv2d+ReLU	3×3	1	1	28×28	512
	Maxpool	2×2	2	0	14×14	512
Block 5	Conv2d+ReLU	3×3	1	1	14×14	512
	Conv2d+ReLU	3×3	1	1	14×14	512
	Conv2d+ReLU	3×3	1	1	14×14	512
	Maxpool	2×2	2	0	7×7	512
Classifier	Fully Connected	–	–	–	1×1	4096
	Fully Connected	–	–	–	1×1	4096
	Fully Connected	–	–	–	1×1	256

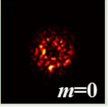

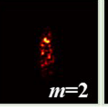

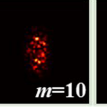
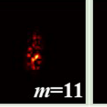
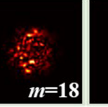
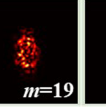
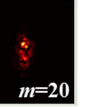









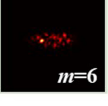


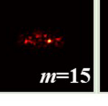





$n = 1$									
unit: mm	$l = 0$			$l = 1$			$l = 2$		
$\delta_y \backslash \delta_x$	0.1	0.2	0.3	0.1	0.2	0.3	0.1	0.2	0.3
0.1	 $m=0$	 $m=1$	 $m=2$	 $m=9$	 $m=10$	 $m=11$	 $m=18$	 $m=19$	 $m=20$
0.2	 $m=3$	 $m=4$	 $m=5$	 $m=12$	 $m=13$	 $m=14$	 $m=21$	 $m=22$	 $m=23$
0.3	 $m=6$	 $m=7$	 $m=8$	 $m=15$	 $m=16$	 $m=17$	 $m=24$	 $m=25$	 $m=26$

Figure S1: Mapping relationship group 1

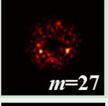








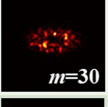





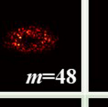








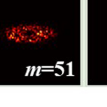


$n = 2$									
unit: mm	$l = 0$			$l = 1$			$l = 2$		
$\delta_y \backslash \delta_x$	0.1	0.2	0.3	0.1	0.2	0.3	0.1	0.2	0.3
0.1	 $m=27$	 $m=28$	 $m=29$	 $m=36$	 $m=37$	 $m=38$	 $m=45$	 $m=46$	 $m=47$
0.2	 $m=30$	 $m=31$	 $m=32$	 $m=39$	 $m=40$	 $m=41$	 $m=48$	 $m=49$	 $m=50$
0.3	 $m=33$	 $m=34$	 $m=35$	 $m=42$	 $m=43$	 $m=44$	 $m=51$	 $m=52$	 $m=53$

Figure S2: Mapping relationship group 2

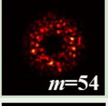





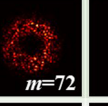















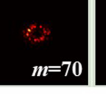

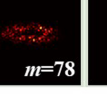


$n = 3$									
unit: mm	$l = 0$			$l = 1$			$l = 2$		
$\delta_y \backslash \delta_x$	0.1	0.2	0.3	0.1	0.2	0.3	0.1	0.2	0.3
0.1	 $m=54$	 $m=55$	 $m=56$	 $m=63$	 $m=64$	 $m=65$	 $m=72$	 $m=73$	 $m=74$
0.2	 $m=57$	 $m=58$	 $m=59$	 $m=66$	 $m=67$	 $m=68$	 $m=75$	 $m=76$	 $m=77$
0.3	 $m=60$	 $m=61$	 $m=62$	 $m=69$	 $m=70$	 $m=71$	 $m=78$	 $m=79$	 $m=80$

Figure S3: Mapping relationship group 3

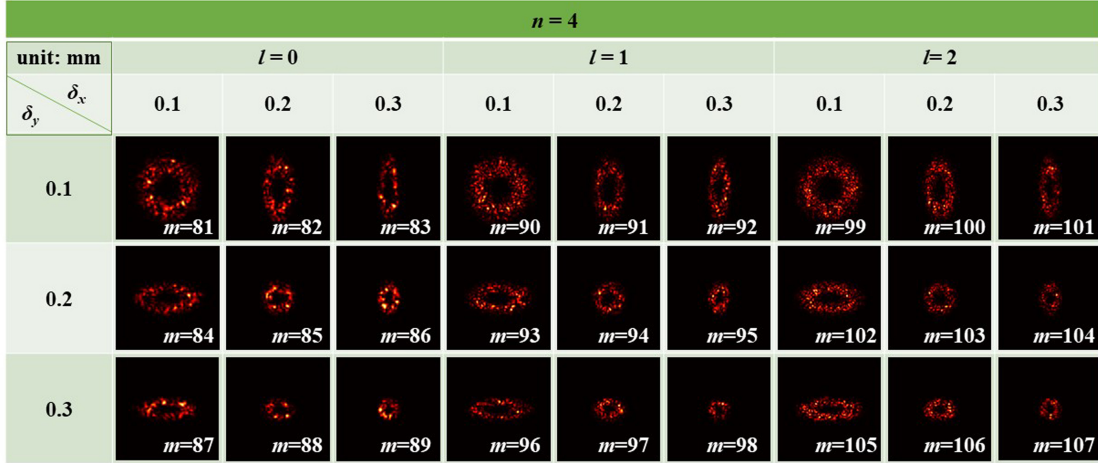


Figure S4: Mapping relationship group 4

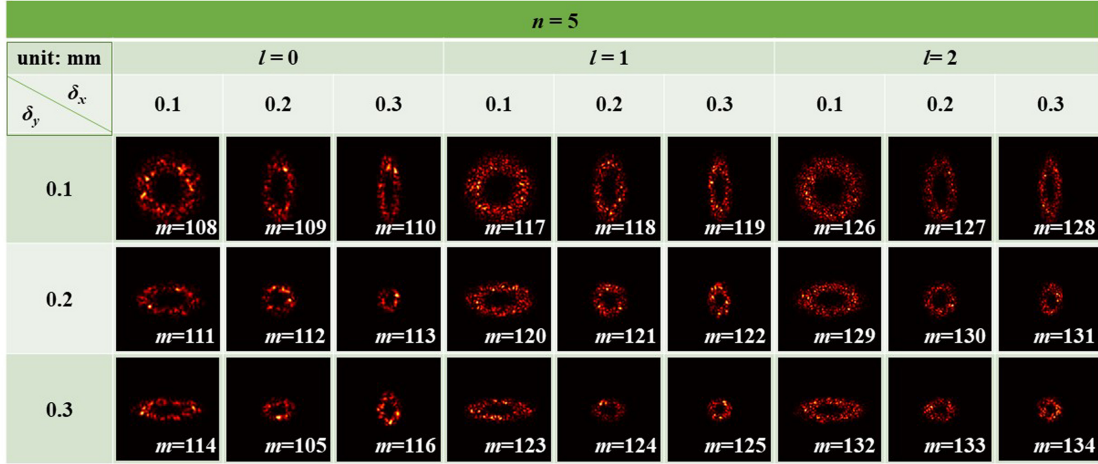


Figure S5: Mapping relationship group 5

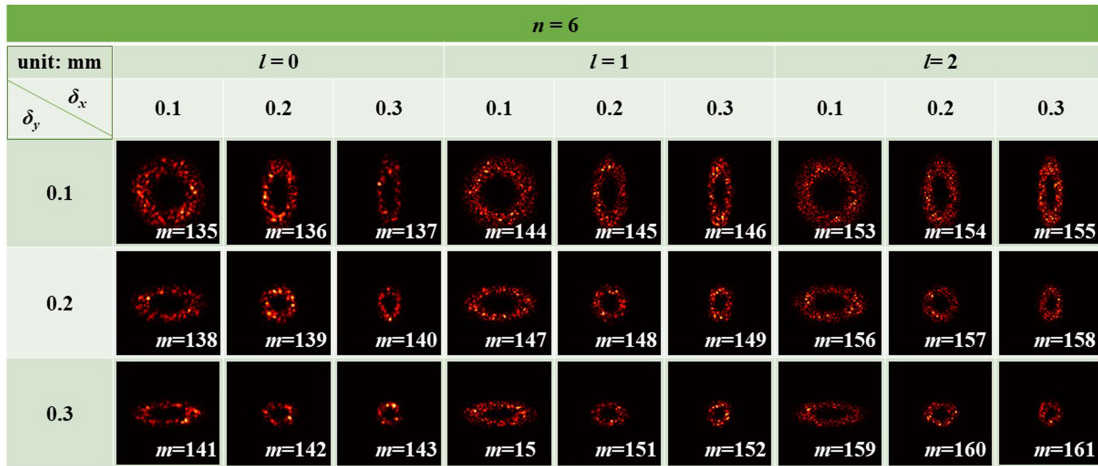


Figure S6: Mapping relationship group 6

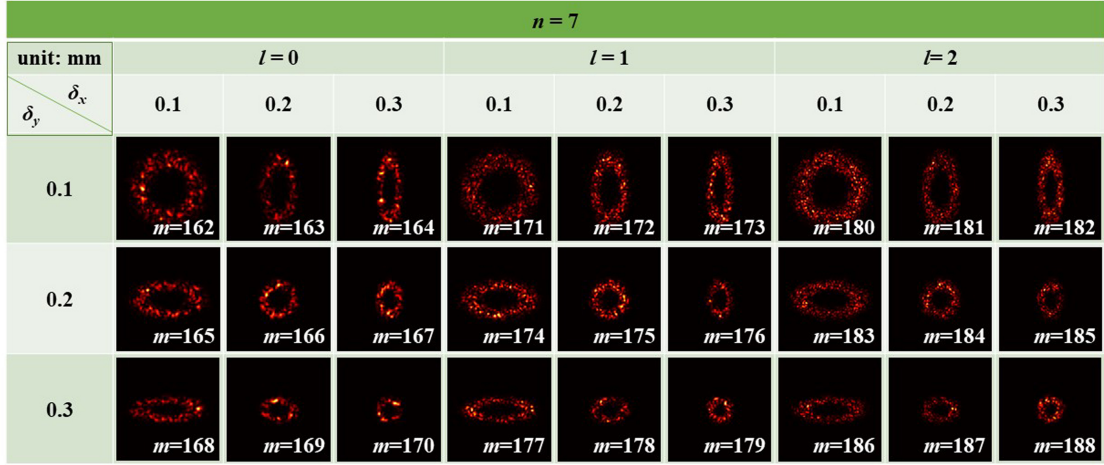


Figure S7: Mapping relationship group 7

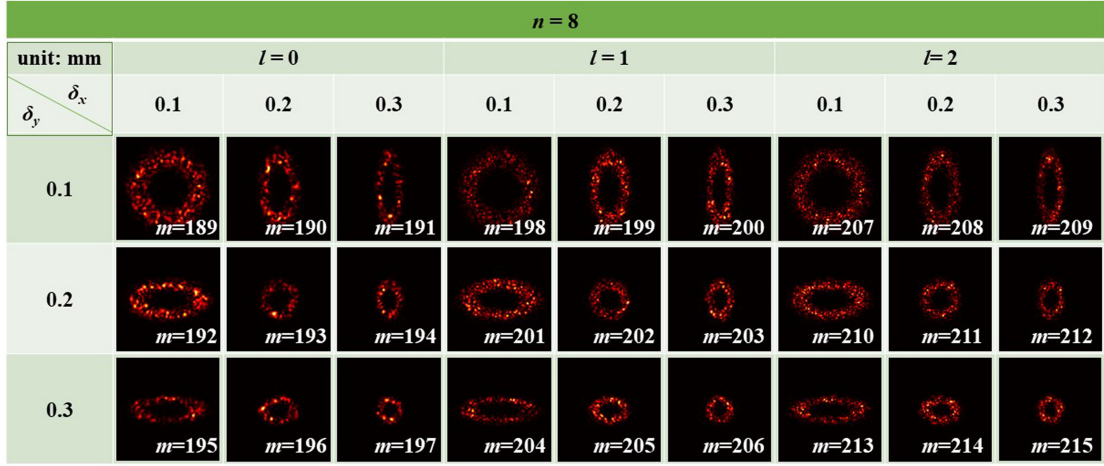


Figure S8: Mapping relationship group 8

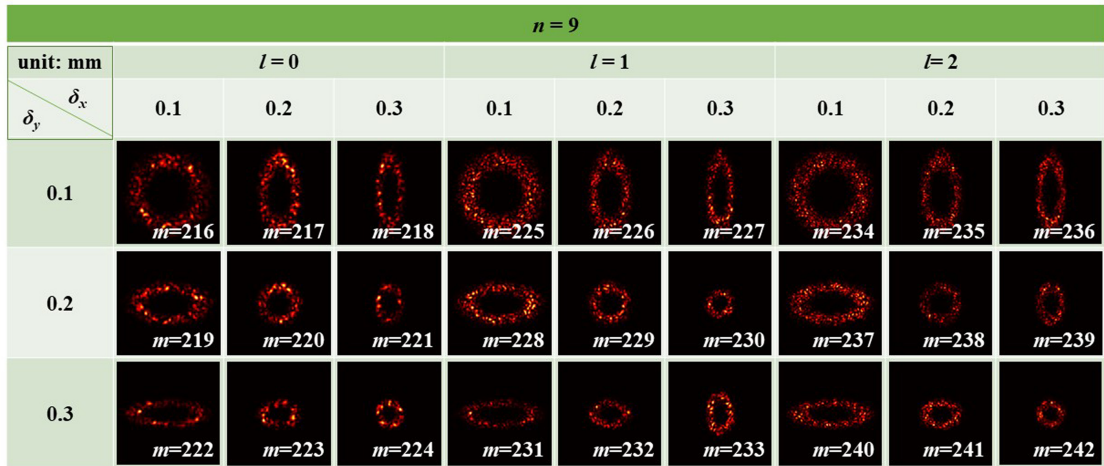


Figure S9: Mapping relationship group 9


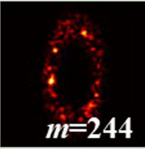
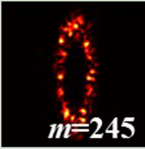
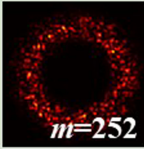
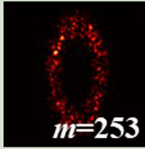
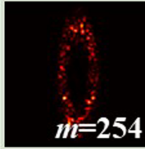
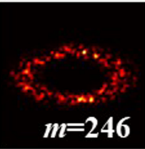

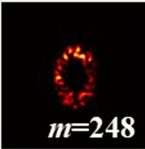
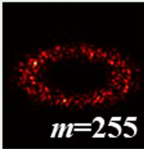
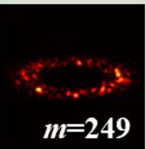
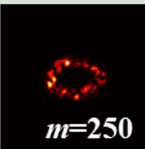
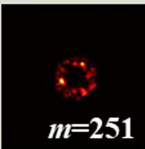
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unit: mm	$l = 0$			$l = 1$		
$\delta_y \backslash \delta_x$	0.1	0.2	0.3	0.1	0.2	0.3
0.1	 $m=243$	 $m=244$	 $m=245$	 $m=252$	 $m=253$	 $m=254$
0.2	 $m=246$	 $m=247$	 $m=248$	 $m=255$		
0.3	 $m=249$	 $m=250$	 $m=251$			

Figure S10: Mapping relationship group 10