Following the recent theoretical predictions given in a paper [PRA 88, 013810 (2013)], we reported on an experimental realization of an image cloning beyond usual diffraction through coherent population trapping (CPT) effect in a hot rubidium vapor. In our experiment, an alphabet image was transferred from a coupling field to a probe field based on the CPT effect. Furthermore, we demonstrated that the cloned probe field carrying the image transmitted without usual diffraction. To our best knowledge, there is no any such an experimental report about images cloning beyond diffraction. We believe this mechanism based on CPT definitely has important applications in image metrology, image processing and biological imaging. © 2013 Optical Society of America.

OCIS Codes: 190.4380; 190.4223.
In our experiments, we used a $\Lambda$-type CPT configuration (see Fig. 1), consisting of two ground states $|1\rangle$ and $|2\rangle$, and one excited state $|3\rangle$. The ground states were given by the Zeeman-degenerate levels of $^{85}$Rb atom ($5S_{1/2}$, $F=3$), the excited state corresponded to the level of $5P_{1/2}$, $F=3$. The coupling and probe fields had the same wavelength of 795 nm, the probe coupled the transition from state $|2\rangle$ to state $|3\rangle$ with a blue-detuned of $\Delta_2$, and the coupling field coupled the atomic transition of $5S_{1/2}(F=3)$ $\rightarrow$ $5P_{1/2}(F=3)$ with a blue-detuned of $\Delta_1$. The coupling was imprinted a real image by a mask of a standard resolution chart (USAF target). The polarizations of coupling and probe were orthogonal, and were combined into a beam through a 5-cm long vapor cell containing $^{85}$Rb atoms by using a polarization beam splitter. The output of coupling and probe fields were separated by using another polarization beam splitter. The structure of coupling and probe fields were monitored by a common camera. The specific parameters of our experiment were recorded as following: The powers of the probe and coupling laser beam were 1.4 mW and 1.5 mW, corresponding to the Rabi frequencies of $\gamma = 8.4\gamma$ and $G=29\gamma$, where $\gamma$ is the decay rate of the upper level $|3\rangle$. The detuning of probe and coupling laser beam was $\Delta_1=361$ MHz and $\Delta_2=375$ MHz respectively. The diameter of the probe beam was 5 mm, and the coupling’s was 1.5 mm, so the probe field completely covered the coupling field. The temperature of vapor cell was heated to be 76°, the atomic density of cell is about $2.5\times10^{12}$ cm$^{-3}$.

Then we input the probe field into the vapor cell along the coupling beam. The obtained spatial structure of probe field at $z=z_0=300$ mm was shown in Fig. 2 (c). The structure of probe at $z=z_0$ was the same as the coupling field at $z=0$ with small blurriness. Obviously, the probes kept the main characters of the input images and showed the good similarities to the input coupling field. This image was beyond the usual diffraction (Fig. 2(c)) compared with the coupling field $z=z_0$ where the strong distortions of spatial information appeared due to the diffraction (Fig. 2(b)). The small blurriness appeared in Fig. 2(c) was still mainly due to the residual diffraction: there existed free space between the front surface of vapor cell and the mask (~45 mm), the diffraction during this distance cannot be controlled via the atomic vapor in our experiment. Another reason was from the unbalanced heating to cell in our experiment, which causes the small modulation on the index refraction, and makes the cloned image somehow blurry. Therefore if could improve the heater system, the quality of cloned image could be improved further. As it is claimed in theoretical paper Ref. 14, the sharpness of the cloned probe image can be increased by a factor 2 as compared to initial feature of the control image. Therefore, one may adjust the position of the CCD to achieve the sharper cloned image. In our system, we didn’t use the 4-f image system to solve the diffraction between the vapor cell and the mask in order to directly illustrate the mechanism of cloning beyond the usual diffraction. In our experiment, the cloning effect beyond the usual diffraction was directly obtained without any 4-f image systems, which was straightforward and more convincing.

In our experiment, we made the coupling beam carry an image of a two-slit structure, and then monitored its spatial information at $z=z_0=300$ mm by using a camera, where $z$ was defined as the distance from the mask to CCD camera. There were clear interference fringes due to its diffraction when the coupling beam propagated in the free space (Here we made the frequency of the coupling field far-detuned with the atomic transitions, so the interaction between the laser and the atoms can be ignored).

![Fig. 2](image_url)

Fig. 2. (Color online) (a) the two-slit structure imprinted on the coupling laser beam. (b) the diffracted image obtained at $z=z_0$. (c) the cloned probe beam monitored at $z=z_0$. $z_0=300$ mm.

Next, we repeated the experiments with two other images: alphabets U and O. We made the coupling beam carrying these two images respectively, and redid the experiments as before. Fig. 3 (a) and

![Fig. 3](image_url)

Fig. 3. (Color online) (a) The alphabet U imprinted on the coupling laser beam. (b) The diffracted image at $z=z_0$. (c) The cloned probe beam at $z=z_0$ (d-f) corresponded to the similar experimental results with the alphabet O. $z_0=300$ mm.
Fig. 3 (d) were the imprinted images onto the coupling field. The propagated images of coupling field at z= z₀ were shown in Fig. 3 (b) and Fig. 3 (e). The cloned probe images at z=z₀ were recorded shown in Fig. 3 (c) and Fig. 3 (f). Obviously, the probes also kept the main characters of the input images and showed the good similarities to the input coupling field except some small blurry. In this process, the transmission intensity of cloned image was ~40 μW.

Fig. 4 (a) The closed image beyond the usual diffraction was shown against the power of probe field. The power of coupling field was about 1.5 mW. (b) The closed image beyond diffraction was shown against the power of coupling field. The power of probe field was about 4 mW. In these figures, the power of probe field 2~6 mW corresponds to the rabi frequency 10γ~17.4γ; the power of coupling field 0~1.5 mW corresponds to the rabi frequency 0γ~29γ. (c) and (d) were the calculated susceptibility as the function of rabi frequencies g and G.

In the following, we checked the cloned image against some experimental parameters. Firstly, we set the power of coupling field to be 1.5 mW and monitored the cloned image against the power of probe field. The results were given by Fig. 4(a). And then, we modulated the power of coupling field to find the relation with the cloned image. The experimental results were shown by Fig. 4(b). With the increment of the coupling power, the effect of cloned images beyond diffraction became better. It seems that there was no strong relation between the power of probe field and the quality of the cloned image. This phenomenon was because the susceptibility became small, which results in the small induced phase and weak absorption. According to Ref. [14], we also derived the density-matrix equation and obtained the susceptibility of $\chi = \chi_{32}$ which was the function of detuning $\Delta_1, \Delta_2$: atomic density; rabi frequencies $G, g$ and decay rate $\gamma$. We characterized the real/imaginary part of the susceptibility $\chi$ against the rabi frequency $g$ shown in Fig. 4(c), where the rabi frequency of coupling field was set to be $G=29\gamma$ and the effective atomic density was $1.0\times10^{12}$ cm$^{-3}$. The curve in Fig. 4(c) illustrated the real/imaginary of susceptibility $\chi$ slowly varied with the different rabi frequency $g$. This point was consistent with our experimental results shown in Fig. 4(a). In the range of $G=10\gamma~0\gamma$, the susceptibility was directly attenuated from 0.5 to 0. From our experimental results in Fig. 4(b), the absorption of probe field 0.9 mW~ 0mW became small and the cloning effect became indistinct. This phenomenon was because the real/imaginary of the susceptibility $\chi$ became small, which results in the small induced phase and weak absorption.

In conclusion, we reported on an experiment about cloning an image through CPT effect and its diffraction effects. With spatially dependent control field, the medium has spatial dependent index of refraction and can effectively transfer the image of the control to the probe beam. The spatial independent phase shift of each plane-wave component of probe field can be controlled by the control field, by which the different phase shift of probe in propagation can be compensated, thus the probe beam transmits without the usual diffraction.

At last, we checked the cloning effect against the atomic density of the $^{85}$Rb in the cell. We used a heater to heat the vapor cell to change the atomic density. The results were shown by Fig. 5 (upper figure). It was shown that the cloned image became unclear with the decrement of the temperature of the vapor cell. This was because the cloning effect beyond diffraction needed more atoms, in such way the medium could be modulated with spatial index of refraction. The calculated curve could illustrate this reason: the real/part of susceptibility of $\chi_{32}$ linearly decreased with the decrement of atomic density which was shown in Fig. 5 (down figure) below where $N=1.0\times10^{12}$ cm$^{-3}$.

In conclusion, we reported on an experiment about cloning an image through CPT effect and its diffraction effects. With spatially dependent control field, the medium has spatial dependent index of refraction and can effectively transfer the image of the control to the probe beam. The spatial independent phase shift of each plane-wave component of probe field can be controlled by the control field, by which the different phase shift of probe in propagation can be compensated, thus the probe beam transmits without the usual diffraction.
We also considered these effects in the different parameters such as: the power of coupling and probe fields and the temperature of vapor cell. Such experimental results clearly showed some interesting properties of CPT on image transfers, and we believe this effect definitely has important applications in image metrology, image processing and biological imaging etc.

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References
1. Bruce E. Cohen, Nature, 467, 407-408 (2010).
2. Eric Lantz, Nature Photonics, 2, 71-72 (2008).
3. Govind P Agrawal, Phys. Rev. Lett. 64, 2487 (1990).
4. Richard R. Moseley, Sara Shepherd, David J. Fulton, Bruce D. Sinclair, and Malcolm H. Dunn. Phys. Rev. Lett. 74, 670–673 (1995).
5. Richard R. Moseley, Sara Shepherd, David J. Fulton, Bruce D. Sinclair, and Malcolm H. Dunn. Phys. Rev. A 53, 408–415 (1996).
6. Ding D S, Zhou Z Y, Shi B S, Zou X B, Guo G C. Optics Communications, 285(7). 1954-1958 (2012).
7. Alexey V. Gorshkov, Liang Jiang, Markus Greiner, Peter Zoller, and Mikhail D. Lukin. Phys. Rev. Lett. 100, 093005 (2008).
8. M. Kiffner, J. Evers, and M. S. Zubairy. Phys. Rev. Lett. 100, 073602 (2008).
9. O. Firstenberg, M. Shuker, N. Davidson, and A. Ron. Phys. Rev. Lett. 102, 043601 (2009).
10. Praveen K. Vudyasetu, David J. Starling, and John C. Howell. Phys. Rev. Lett. 102, 123602 (2009).
11. H. Li, V. A. Sautenkov, M. M. Kash, A. V. Sokolov, G. R. Welch, Y. V. Rostovtsev, M. S. Zubairy, and M. O. Scully, Phys. Rev. A 78, 013803 (2008).
12. T. N. Dey, and G. S. Agarwal, OPTICS LETTERS 34, 3199 (2013).
13. Tarak N. Dey and Jorg Evers, Phys. Rev. A 84, 043842 (2011).
14. Onkar N. Verma, Lida Zhang, Jorg Evers, and Tarak N. Dey, Phys. Rev. A 88, 013810 (2013).
15. Firstenberg O, Shuker M, Davidson N, A. Ron. Physical Review letters, 2009, 102(4): 043601.
16. Firstenberg O, London P, Shuker M, A. Ron, Davidson N. Nature Physics, 2009, 5(9): 665-668.
References
1. Bruce E. Cohen, “Biological imaging: Beyond fluorescence” Nature, 467, 407-408 (2010).
2. Eric Lantz, “Medical imaging: Retracing random paths” Nature Photonics, 2, 71-72 (2008).
3. Govind P. Agrawal, Induced focusing of optical beams in self-defocusing nonlinear media, Phys. Rev. Lett. 64, 2487 (1990).
4. Richard R. Moseley, Sara Shepherd, David J. Fulton, Bruce D. Sinclair, and Malcolm H. Dunn “Spatial Consequences of Electromagnetically Induced Transparency: Observation of Electromagnetically Induced Focusing” Phys. Rev. Lett. 74, 670–673 (1995).
5. Richard R. Moseley, Sara Shepherd, David J. Fulton, Bruce D. Sinclair, and Malcolm H. Dunn “Electromagnetically-induced focusing” Phys. Rev. A 53, 408–415 (1996).
6. Ding D S, Zhou Z Y, Shi B S, Zou X B, Guo G C. "Modulating an image through a non-material lens in a vapor cell", Optics Communications, 285(7), 1954-1958 (2012).
7. Alexey V. Gorshkov, Liang Jiang, Markus Greiner, Peter Zoller, and Mikhail D. Lukin “Coherent Quantum Optical Control with Subwavelength Resolution” Phys. Rev. Lett. 100, 093005 (2008).
8. M. Kiffner, J. Evers, and M. S. Zubairy “Resonant Interferometric Lithography beyond the Diffraction Limit” Phys. Rev. Lett. 100, 073602 (2008).
9. O. Firstenberg, M. Shuker, N. Davidson, and A. Ron “Elimination of the Diffraction of Arbitrary Images Imprinted on Slow Light”. Phys. Rev. Lett. 102, 043601 (2009).
10. Praveen K. Vudyasetu, David J. Starling, and John C. Howell. “All Optical Waveguiding in a Coherent Atomic Rubidium Vapor” Phys. Rev. Lett. 102, 123602 (2009).
11. H. Li, V. A. Sautenkov, M. M. Rash, A. V. Sokolov, G.R. Welch, Y. V. Rostovtsev, M. S. Zubairy, and M. O. Scully, Optical imaging beyond the diffraction limit via dark states. Phys. Rev. A 78, 013803 (2008).
12. T. N. Dey, and G. S. Agarwal, "Subdiffraction propagation of images using saturated absorption of optical transition", OPTICS LETTERS 34, 3199 (2013).
13. Tarak N. Dey and Jörg Evers, "Nondiffracting optical beams in a three-level Raman system", Phys. Rev. A 84, 043842 (2011).
14. Onkar N. Verma, Lida Zhang, Jörg Evers, and Tarak N. Dey, “Optical cloning of arbitrary images beyond the diffraction limits”. Phys. Rev A 88, 013810 (2013).
15. Firstenberg O, Shuker M, Davidson N, A. Ron. “Elimination of the diffraction of arbitrary images imprinted on slow light”. Physical Review letters, 2009, 102(4): 043601.
16. Firstenberg O, London P, Shuker M, A. Ron, Davidson N. “Elimination, reversal and directional bias of optical diffraction”. Nature Physics, 2009, 5(9): 665-668.