Secure Data Storage by Three-dimensional Absorbers in Highly Scattering Volume Medium

Osamu Matoba, Shinichiro Matsuki, and Kouichi Nitta
Department of Computer Science and Systems Engineering, Kobe University,
Rokkodai 1-1, Nada, Kobe 657-8501, JAPAN
matoba@kobe-u.ac.jp

Abstract. A novel data storage in a volume medium with highly scattering coefficient is proposed for data security application. Three-dimensional absorbers are used as data. These absorbers can not be measured by interferometer when the scattering in a volume medium is strong enough. We present a method to reconstruct three-dimensional absorbers and present numerical results to show the effectiveness of the proposed data storage.

1. Introduction
In highly developed information society, information security is one of important issues. Especially, secure data storage and personal identification are critical issues. Optical methods can realize large data storage and remote access to the data with security[1-3]. Biometrics is used to identify the person with extremely high accuracy. The information to be used in the identification can not be changed, it becomes critical problems if the information is stolen. For commercial use, it is required that cheap, ease, and reusable method for the identification and data storage is preferred.

In this paper, we present the secure data storage by use of three-dimensional(3D) absorbers in a highly scattering medium. The person who knows the distribution of scattering coefficient can reconstruct 3D absorbers by solving inverse problem with pairs of input and output intensity distribution. Numerical results are presented to show the feasibility of the proposed system.

2. Secure data storage with 3D absorbers in a highly scattering medium
Figure 1 shows a concept of secure 3D data storage with 3D absorbers in a highly scattering volume medium. The scattering medium can make the system secure. These 3D absorbers cannot be measured by interferometer when the scattering is strong enough. The phase information of the propagated light is lost due to multiple scattering. Output intensity decreases by 3D absorbers, but it is difficult to know a number of 3D absorbers in a volume medium and their 3D positions. The size, position, and number of 3D absorbers can be used as secure information. The absorption and scattering coefficient distributions are reconstructed numerically by pairs of input and output intensity distributions and a weight function. The weight function gives the output intensity change when scattering coefficient or absorption coefficient changes in a volume medium. The estimation of weight function is a key to solve the inverse problem.
We present a method to reconstruct the 3D absorbers. Figure 2 shows the procedure of the reconstruction algorithm. In the measurement, we can obtain input and output intensity distributions. We also have the information of scattering coefficient distribution as the correct user. From this information, we can make a model of the reference medium with uniform absorption distribution to estimate the 3D absorbers. In the estimation, the output intensity distribution is calculated by solving numerical diffusion equation. This output intensity distribution is different from the measured output intensity distribution. The reconstruction algorithm can modify the reference object to reduce the difference between the measured and calculated output intensity.

**Figure 1.** Concept of proposed data storage using 3D absorbers in a highly scattering medium.

**Figure 2.** Schematics of reconstruction of 3D absorption distribution.

### 3. Estimation of 3D absorbers

As shown in Figure 2, 3D absorption distribution is reconstructed by using a weight function and the intensity difference[4-7]. The weight function gives the change rate of output intensity when the
absorption changes. In the following subsections, we present a calculation method of propagated light in scattering medium and a reconstruction method.

3.1. Calculation of scattered light
In a highly scattering medium, the light propagation can be calculated by solving the diffusion equation. The diffusion equation in frequency domain [4] is described as

$$\nabla^2 u(r) + k^2(r)u(r) = -S(r)$$  \hspace{1cm} (1)

where

$$k(r) = [-\mu_a(r)/D(r) + i\omega/vD(r)]^{1/2}$$  \hspace{1cm} (2)

and

$$D(r) = \left\{ \frac{3}{\mu_a(r) + \mu_s(r)} \right\}^{-1}$$  \hspace{1cm} (3)

In Eqs. (1), (2), and (3), \(u(r)\) denotes fluence rate, \(S(r)\) input light source, \(\omega\) angular frequency of intensity modulation, \(v\) speed of light, \(\mu_e\) effective scattering coefficient, \(\mu_a\) absorption coefficient.

There are many methods to solve numerically the diffusion equation. Here we use finite difference approach as used in beam propagation method [8]. Let \(u(r) = \phi(x,z) \exp(-ik_0z)\) where \(k_0\) a complex wave number in background and \(z\) is the propagation direction. Eq. (1) is changed as the following discrete equation.

$$-\alpha^w_{l+1} \phi^l_{p-1} + \left\{ -\alpha^s_x \phi^l_{p+1} + \frac{4ik_0}{\Delta z} - ((k^l_p)^2 - k_0^2) \right\} \phi^l_p - \alpha^s_x \phi^l_{p-1} = \alpha^w_{l} \phi^l_{p-1} + \left\{ \alpha^s_x + \frac{4ik_0}{\Delta z} + ((k^l_p)^2 - k_0^2) \right\} \phi^l_{p+1}$$  \hspace{1cm} (4)

In Eq. (4), \(l\) denotes layer number, \(p\) denotes pixel number, \(\alpha^w = 1/\Delta x^2\), \(\alpha^s_x = -2/\Delta x^2\), \(\Delta x\) and \(\Delta z\) denote the pixel sizes along the \(x\) and \(z\) axes.

3.2. Reconstruction
We present a reconstruction method to solve the inverse problem. Here the reference object is assumed to be homogeneous scattering medium. Let \(u_o\) and \(u_b\) be output fluence rate in measured and reference object, respectively. The difference of fluence rate is

$$\Delta u = u_o - u_b$$  \hspace{1cm} (5)

The object function is described by using complex wave numbers in the measured and reference objects:

$$o(r) = k^2(r) - k_0^2$$  \hspace{1cm} (6)

By taking linear perturbation approach in the scale wave equation, we obtain the following equation:

$$WO = \Delta u$$  \hspace{1cm} (7)

In Eq. (7), \(W\) is a weight matrix. The element \(W_{ij}\) is described as

$$W_{ij} = G(r_{ai}, r_j)u(r_j, r_{ai})\delta_v$$  \hspace{1cm} (8)

In Eq. (8), \(G\) is the Green’s function of the homogeneous background and \(r_j\) is a voxel in the medium, \(\delta_v\) is a voxel volume. By solving Eq. (7), we can estimate \(k(r)\).
4. Numerical results

We present numerical results to show the feasibility of the proposed method. First, reconstruction of single absorber is presented. Next, reconstruction of two adjacent absorbers is evaluated and then we discuss the density of the absorbers. In both cases, the scattering coefficient is uniform in a volume medium. In the last topic, more complex structure in scattering coefficient distribution is discussed to achieve a higher level of security.

4.1. Single absorber

To apply this technique to credit card or papers, the thickness of the volume medium should be thin. For simplicity, two-dimensional model is analyzed. The size of the medium is 4.0mm×1.0mm, a pixel size is 80μm×20μm, uniform absorption coefficient μ_a=0.1mm⁻¹, and the absorption coefficient of 3D absorbers μ_a=2.0mm⁻¹. The size of absorber is 160μm×160μm. By using 7 input point sources and 50 detectors, the reconstruction result is presented in Figure 3. The absorber was reconstructed successfully.

4.2 Two absorbers

To estimate the storage capacity, more absorbers should be used and reconstruction should be evaluated. Here we evaluate the reconstruction ability when two absorbers are located. Contrast of absorption coefficients of objects and cross-talk noise, a/b, is evaluated. Figure 4 shows the contrast as a function of distance. When the contrast is larger than two, the distance should be longer than twice of the absorber size.

![Figure 3. Reconstruction of single absorber; (a) original and (b) reconstruction.](image)

![Figure 4. Contrast as a function of distance between two absorbers.](image)
4.3 Complicated background

In sections 3.1 and 3.2, volume scattering medium is homogeneous. To achieve a higher level of security, more complicated structure in scattering coefficient distribution is required. Here we use two layers with different scattering coefficients. Figures 5(a) and (b) show a scattering coefficient distribution with two different scattering coefficients of 10mm\(^{-1}\) and 27mm\(^{-1}\) and two absorbers, respectively. When the correct scattering coefficient distribution is used, the reconstruction result is good as shown in Figure 5(c). When the reconstruction is executed by uniform scattering coefficient with 10mm\(^{-1}\), the result is shown in Figure 5(d). One of the absorbers was not reconstructed. This result indicates that the scattering coefficient distribution can work as key to solve the inverse problem.

![Figure 5](image)

**Figure 5.** Reconstructions of 3D absorbers in complex background; (a) scattering coefficient distribution, (b) two 3D absorbers, and reconstructions with (c) accurate and (d) inaccurate scattering coefficient distributions.

4. Conclusion

We have presented an optical secure data storage medium using on 3D absorbers in a highly scattering medium. The results showed that the authorized user can reconstruct 3D absorbers using the correct scattering coefficient distribution. The information of 3D absorbers can be secure by strong scattering because the interferometer could not be applied. More complicated structure makes the system more secure.

References

[1] Javidi B ed. 2004 Optical and Digital Techniques for Information Security (New York: Springer)
[2] Refregier P and Javidi B 1995 *Opt. Lett.* 20, 767
[3] Matoba O, Sawasaki T, Nakajima K and Nitta K 2007 *Journal of Physics: Conference Series* 77, 012009
[4] Yao Y, Wang Y, Pei Y, Zhu W and Barbour R.L. 1997 *J. Opt. Soc. Am. A* 14, 325
[5] Nitta K, Matoba O and Yoshimura T 2007 *IEEJ Trans. FM* 127, 397
[6] Yamamura T, Nitta K and Matoba O 2007 *Technical Digest of The 13th Microoptics Conference (MOC’07)* 294
[7] Nitta K, Doi Y, Goto A and Matoba O *Jpn. J. Appl. Phys.* Submitted
[8] Chung Y and Dagli N 1990 *IEEE J. Quantum Electron.* QE-26, 1335