Physics of Wave Processes and Radio Systems
2024, vol. 27, no. 2, pp. 38–44

DOI 10.18469/1810-3189.2024.27.2.38-44
UDC 535.1
Original Research

Received 18 December 2023
Accepted 19 January 2024
Published 29 June 2024

Double wavefront reversal during six-wave interaction on Kerr nonlinearity in a waveguide with infinitely conducting surfaces

Valery V. Ivakhnik, Darkhan R. Kapizov, Vladimir I. Nikonov

Samara National Research University
34, Moskovskoye shosse,
Samara, 443086, Russia

Abstract – **Background.** Generation of a wave with a double reversed wavefront in multimode waveguides increases the efficiency of six-wave radiation converters and expands the possibilities of its use in adaptive optics problems and the conversion of complex spatially inhomogeneous waves. **Aim.** The quality of double wavefront reversal during six-wave interaction in a waveguide with infinitely conducting surfaces with Kerr nonlinearity is analyzed for the ratio of the wave numbers of the pump waves equal to 2 and 0,5, and the condition that one of the pump waves excites the zero mode of the waveguide, and the amplitude distribution of the other pump wave excites the edges of the waveguide are described by a Gaussian function. **Methods.** The influence of pump wave parameters on the half-width and contrast of the amplitude modulus of the object wave was studied using numerical methods. A wave from a point source located on the front face of the waveguide was used as a signal wave. **Results.** The dependences of the half-width and contrast of the amplitude modulus of the object wave on the ratio between the width of the waveguide and the width of the Gaussian pump wave are obtained. **Conclusion.** It is shown that the maximum change in the characteristics of a wave with a double reversed wavefront is observed when the width of the Gaussian pump waves changes in the range from 0,3 to 2 half-widths of the waveguide.

Keywords – six-wave radiation converter; double wavefront reversal; Kerr nonlinearity.

Introduction

The presence of fifth-order nonlinear susceptibility in the medium makes it possible, when realizing six-wave interaction in the form of $\omega_1 + \omega_1 - \omega_1 - \omega_1 + \omega_2 = \omega_2$, to obtain a wave whose complex amplitude is proportional to the square of the complex-conjugate amplitude of the signal wave (a wave with a Doubled Reversed Wavefront (DRWF)) [1–2]. Wave generation with DRWF expands the possibilities of using six-wave radiation converters in the tasks of phase distortion correction, conversion of complex spatially inhomogeneous waves, etc. [3].

In order to increase the efficiency of multiwavelength converters, it is reasonable to switch from the consideration of interaction in transverse dimensionally unbounded media to the consideration of interaction in waveguides [4–6]. At the same time, when it comes to the transformation of complex spatially inhomogeneous fields, there is always the problem of the quality of the transformation, i.e. about the correspondence between the complex amplitudes of the signal wave and the wave with a doubled reversed wavefront [7–8]

Herein, we analyze the effect on the quality of the DRWF at six-wave interaction in a waveguide with infinite conducting surfaces filled with a medium with Kerr nonlinearity, the spatial structure of the pump waves, provided that the ratio of the wave numbers of the pump waves is a multiple of integer or semi-integer.

1. Principal Part

We assume that two pump waves with complex amplitudes A_1 and A_2, frequencies ω_1 and ω_2, and a signal wave with complex amplitude A_3 at frequency ω_1 propagate in a waveguide located between the planes towards each other. Nonlinear polarization $(A_1 A_3^*)^2 A_2$ is induced in the medium, which is the source of an object wave with a complex amplitude A_6 at the frequency ω_2. The phase of the object wave is proportional to the doubled phase of the signal wave taken with a minus sign (a wave with a Doubled Reversed Wavefront).

In the approximation of a given field by pump waves, at a small conversion factor, without taking into account the change of the refractive index due to the self-interaction of pump waves, the amplitude of the object wave with DRWF at the front edge of the waveguide is [9].

✉ nikon5919@mail.ru (*Vladimir I. Nikonov*)

$$A_6(x,z=0)=\sum_{r=0}^{N_2} a_{6r}\tilde{f}_r(x,\omega_2)= \tag{1}$$
$$=-i\frac{g\ell}{2}\sum_{r=0}^{N_2}\frac{\tilde{f}_r(x,\omega_2)}{\beta_r}\sum_{p=0}^{N_1}\sum_{p'=0}^{N_1}\sum_{m=0}^{N_2}\sum_{s=0}^{N_1}\sum_{s'=0}^{N_1}a_{1p}^{(0)}a_{1p'}^{(0)}\times$$
$$\times a_{2m}^{(0)}a_{3s}^{(0)*}a_{3s'}^{(0)*}\gamma_{pp'mss'r}\,\mathrm{sinc}\left(\frac{\Delta_{pp'mss'r}\ell}{2}\right)\times$$
$$\times\exp\left(-i\frac{\Delta_{pp'mss'r}\ell}{2}\right).$$

Here $g=\frac{30\pi\omega_2^2}{c^2}\chi^{(5)}$; $\chi^{(5)}$ is the nonlinear susceptibility of the fifth order; $a_{1p}^{(0)}$, $a_{3s}^{(0)}$ are the coefficients in the decomposition of the amplitudes of the first pump wave, the signal wave on the leading edge according to the modes of the waveguide; $a_{2m}^{(0)}$ is the coefficients in the decomposition of the amplitude of the second pump wave on the back face according to the modes of the waveguide; $\tilde{f}_r(x,\omega_{1.2})$ and $\beta_r(\omega_{1,2})$ are the transverse component and the propagation constant of the r-th mode of the waveguide; N_1 and N_2 are the number of waveguide modes at frequencies ω_1 and ω_2, and taken into account when calculating the amplitude of a wave with a DRWF;

$$\Delta_{pp'mss'r}=\beta_p+\beta_{p'}-\beta_m-\beta_s^*-\beta_{s'}^*+\beta_r$$

is the wave detuning;

$$\gamma_{pp'mss'r}=\int\tilde{f}_p(x,\omega_1)\tilde{f}_{p'}(x,\omega_1)\tilde{f}_m(x,\omega_2)\times$$
$$\times\tilde{f}_s(x,\omega_1)\tilde{f}_{s'}(x,\omega_1)\tilde{f}_r(x,\omega_2)dx$$

is the overlap integral.

For a signal wave from a point source, ($A_3(x,z=0)=\delta(x-x_0)$, x_0 is the coordinate that determines the displacement of the point source relative to the axis of the waveguide) in the case of long waveguides, that is, we consider the condition $\mathrm{Re}(\Delta_{pp'mss'r})\ell\gg 1$ to be fulfilled if $\mathrm{Re}(\Delta_{pp'mss'r})\neq 0$, the expression for the amplitude of the object wave takes the form of

$$G(x,x_0,z=0)=-i\frac{g\ell}{2}\sum_{r=0}^{N_2}\frac{\tilde{f}_r(x,\omega_2)}{\beta_r}\times \tag{2}$$
$$\times\sum_{p=0}^{N_1}\sum_{p'=0}^{N_1}\sum_{m=0}^{N_2}\sum_{s=0}^{N_1}a_{1p}^{(0)}a_{1p'}^{(0)}a_{2m}^{(0)}\tilde{f}_s(x_0,\omega_1)\times$$
$$\times\tilde{f}_{s'}(x_0,\omega_1)\gamma_{pp'mss'r}.$$

As in the case of considering the quality of wavefront reversal in four-wave interaction [10–11], we will refer to the function $G(x,x_0,z=0)$ as the Point-Spread Function (PSF).

Note that while at four-wave interaction the knowledge of PSF fully describes the accuracy of RWF, the nonlinear nature of the relationship between the complex amplitude of the object wave and the complex amplitude of the signal wave allows using PSF to speak only qualitatively about the accuracy of DRWF.

As a waveguide we shall consider a two-dimensional waveguide with infinitely conducting surfaces located at a distance $2a$ from each other, filled with a medium with refractive index n_1. The modes of such a waveguide are functions [12]

$$\tilde{f}_r(x)=\frac{1}{\sqrt{a}}\sin\left[\frac{\pi(r+1)}{2a}(x+a)\right]. \tag{3}$$

For the near-axis modes of the waveguide the propagation constant of the r-th mode is

$$\beta_r(\omega_{1,2})\approx k_{1,2}-\frac{1}{2k_{1,2}}\left[\frac{\pi(r+1)}{2a}\right]^2, \tag{4}$$

where $k_{1,2}=\frac{\omega_{1,2}}{c}n_1(\omega_{1,2})$ is the wave number.

The condition of the six-wave interaction with DRWF in a long waveguide with infinite conducting surfaces is written as follows

$$h\left[(p+1)^2+(p'+1)^2-(s+1)^2-(s'+1)^2\right]- \tag{5}$$
$$-\left[(m+1)^2-(r+1)^2\right]=0.$$

Here $h=k_2/k_1$.

In the case when the ratio of the pump wave numbers is not equal to an integer or a ratio of integers, condition (5) is satisfied only when the mode number of the objective wave coincides with the mode number of the second pump wave ($r=m$). This reduces the number of combinations of waveguide modes involved in the formation of the wave with the DRWF.

Fig. 1 shows characteristic normalized graphs of the dependence of the moduli of the blur functions of a point located on the axis of the waveguide ($\tilde{G}=\left|\frac{G(x,x_0=0,z=0)}{G_{\max}}\right|$, $G_{\max}$ – is the maximum value of the function) on the normalized transverse coordinate, provided that the first pump wave is single–mode with the mode number $p=0$, and the amplitude of the second pump wave on the back face of the waveguide is described by the Gaussian function $A_2(x,z=\ell)=\exp(-x^2/b^2)$. Here b is the pump wavelength.

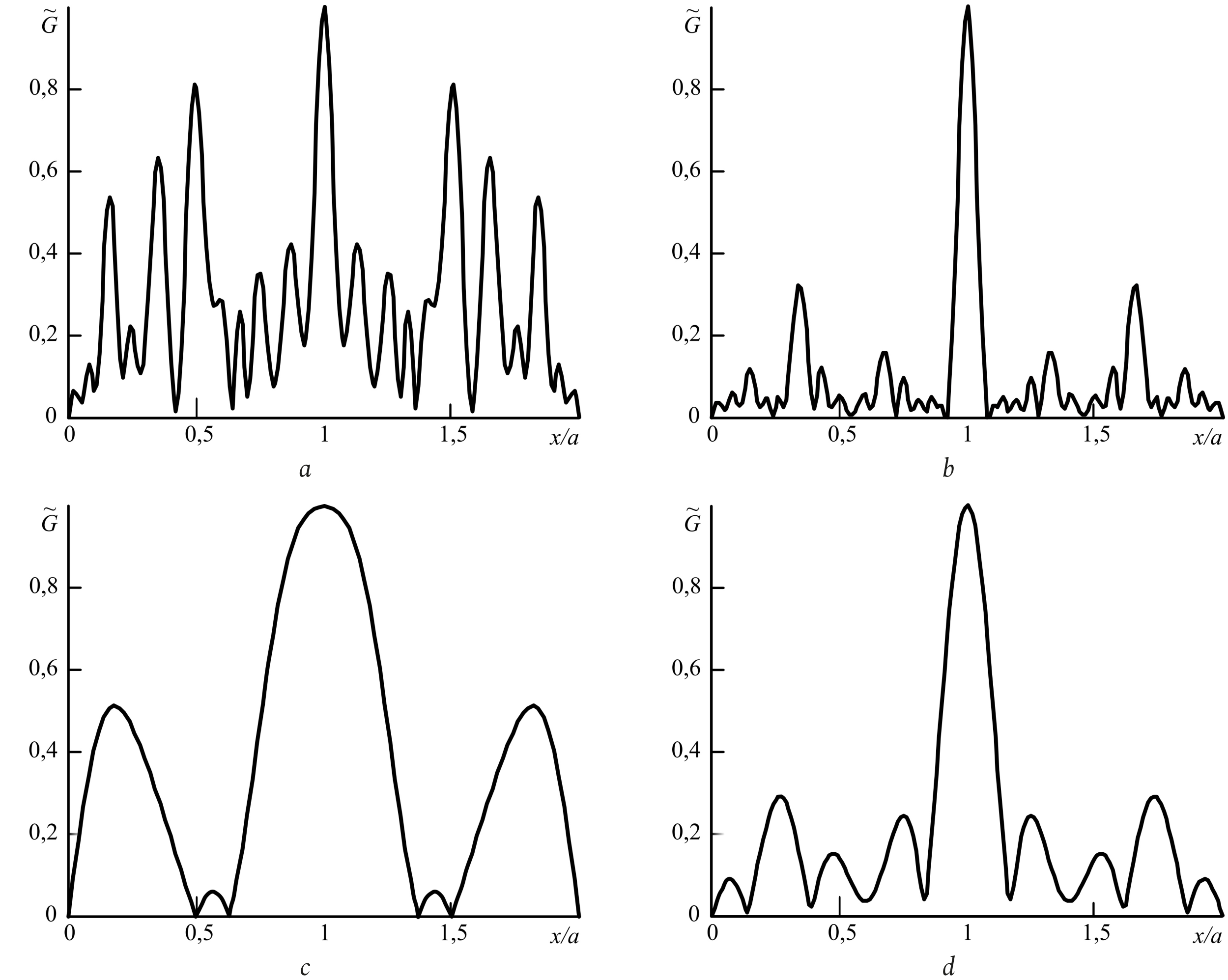

Fig. 1. Dependence of the PSF modulus on the transverse coordinate at $h = 2$ (*a*, *b*), 0,5 (*c*, *d*): the first pump wave is single-mode with the mode number $p = 0$, the amplitude of the second pump wave changes according to the Gaussian law, $a/b = 1$ (*a*, *c*), 8 (*b*, *d*)

Рис. 1. Зависимость модуля ФРТ от поперечной координаты при $h = 2$ (*а*, *б*), 0,5 (*в*, *г*): первая волна накачки одномодовая с номером моды $p = 0$, амплитуда второй волны накачки меняется по гауссову закону, $a/b = 1$ (*а*, *в*), 8 (*б*, *г*)

Similar graphs of the dependence of the moduli of the point blur functions are observed when the second pump wave is single-mode with the mode number $m = 0$, and the amplitude of the first pump wave on the leading edge of the waveguide is described by the Gaussian function $A_1(x, z = 0) = \exp(-x^2 / b^2)$.

In calculating the PSF modulus, 20 modes of the signal wave, the first pump wave, and 20h modes of the object wave, the second pump wave, were considered.

Both when considering the Gaussian structure of the first pumping wave and when considering the Gaussian structure of the second pumping wave, the PSF modulus consists of central and side maxima. At a fixed frequency of the first pump wave, increasing the frequency of the second pump wave increases the number of side maxima, decreases the width of the central maximum. Changing the width of the Gaussian pump wave changes the ratio between the central and side maxima, affecting the width of the central maximum.

The quantitative parameters characterizing the quality of the DRWF may consist of the half-width of the central maximum of the PSF modulus (Δx), determined from the solution of the equation

$$\left|G\left(x = \Delta x, x_0 = 0, z = 0\right)\right| = \frac{1}{2}\left|G\left(x = a, x_0 = 0, z = 0\right)\right|, \quad (6)$$

and the contrast of the PSF modulus, defined as the ratio of the value of the central maximum to the largest value of one of the side maximums (K).

It is obvious that the use of the half-width of the central maximum of the PSF modulus for the analysis of the quality of the DRWF assumes the presence of a pronounced central maximum. Otherwise, which is observed, for example, at $h = 0{,}5$ and $b > a$, it is not possible to use this parameter to analyze the quality of DRWF.

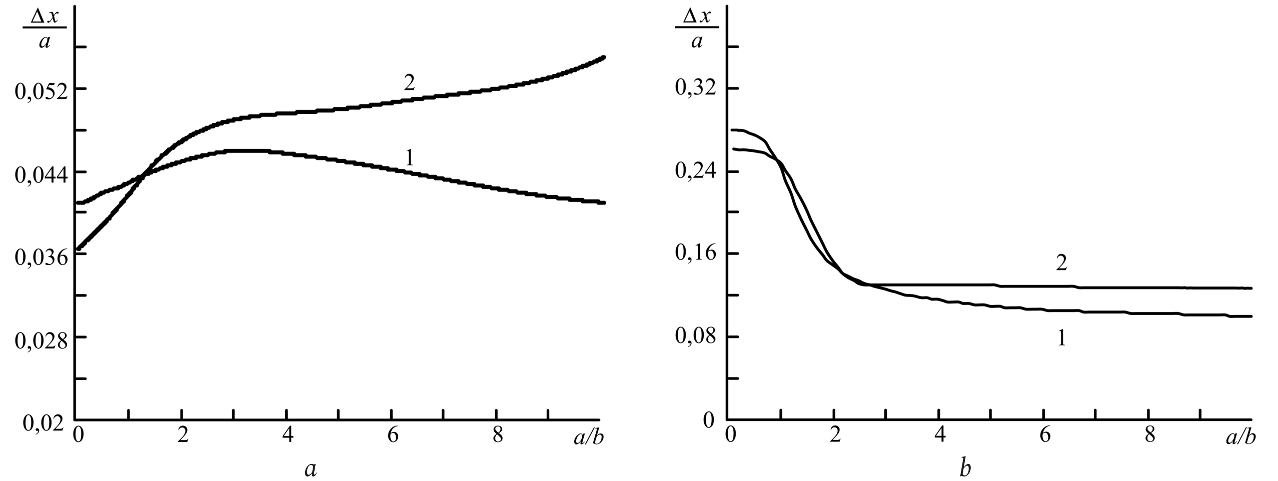

Fig. 2. Dependence of the half-width of the central maximum of the PSF module on the width of the Gaussian pump wave: the second pump wave is Gaussian, the first pump wave is single-mode (1); the first pump wave is Gaussian, the second pump wave is single-mode (2) at $h = 2$ (*a*), 0,5 (*b*)

Рис. 2. Зависимость полуширины центрального максимума модуля ФРТ от ширины гауссовой волны накачки: вторая волна накачки гауссова, первая волна накачки одномодовая (1); первая волна накачки гауссова, вторая волна накачки одномодовая (2) при $h = 2$ (*а*), 0,5 (*б*)

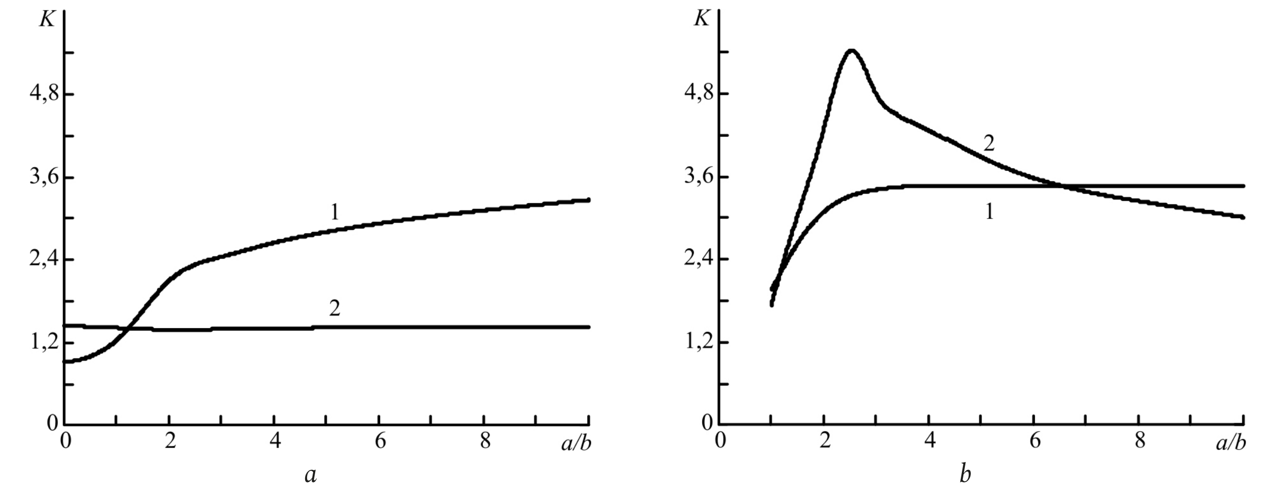

Fig. 3. Dependence of the contrast of the PSF module on the width of the Gaussian pump wave: the second pump wave is Gaussian, the first pump wave is single-mode (1); the first pump wave is Gaussian, the second pump wave is single-mode (2) at $h = 2$ (*a*), 0,5 (*b*)

Рис. 3. Зависимость контраста модуля ФРТ от ширины гауссовой волны накачки: вторая волна накачки гауссова, первая волна накачки одномодовая (1); первая волна накачки гауссова, вторая волна накачки одномодовая (2) при $h = 2$ (*а*), 0,5 (*б*)

Improving the quality of the DRWF involves both narrowing the central maximum and increasing the contrast of the PSF modulus.

In the case of $h = 2,$ with a decrease in the width of the second Gaussian pump wave under the condition of a single-mode first pump wave with the mode number $p = 0,$ the half-width of the central maximum of the PSF modulus changes slightly and increases monotonously with a decrease in the half-width of the first Gaussian pump wave under the condition of a single-mode second pump wave with the mode number $m = 0$ (Fig. 2, *a*). In the range of variation of the width of the second Gaussian pump wave from $b = 0{,}125a$ to $b = 1{,}25a,$ the half-width of the central maximum of the PSF modulus varies from $0{,}043a$ to $0{,}047a,$ and when the width of the first pump wave is varied in this range, it increases from $0{,}041a$ to $0{,}052a.$

The contrast of the PSF modulus increases with decreasing width of the second Gaussian pump wave under the condition of single-mode first pump wave and changes weakly with changing width of the first Gaussian pump wave under the condition of single-mode second pump wave (Fig. 3, *a*).

In the case of $h = 0{,}5,$ as the width of either the first or second Gaussian pump waves decreases, the half-width of the central maximum of the PSF modulus decreases (Fig. 2, *b*). In the range of variation b

from $0,125a$ to $1,25a$, the half-width of the central maximum of the PSF modulus decreases from $0,26a$ to $0,13a$, provided that the amplitude of the first pump wave varies according to the Gaussian law, from $0,26a$ to $0,10a$, provided that the amplitude of the second pump wave varies according to the Gaussian law.

The contrast of the PSF modulus in the range of variation b from $0,125a$ to $1,25a$, with decreasing width of the second Gaussian pump wave, increases and comes to a constant value equal to 3,46. As the width of the first Gaussian pump wave decreases, the contrast of the PSF modulus increases at first, reaches a maximum value of 5,41, and then slowly decreases (Fig. 3, *b*).

The maximum value of the contrast change rate, the half-width of the central maximum of the PSF modulus for both $h=2$, and $h=0,5$, is observed in the range of variation in the width of Gaussian pump waves from $b=0,3a$ to $b=2a$. With a further decrease in the width of the Gaussian pump wave, the rates of change of both the half-width of the central maximum and the contrast of the PSF modulus decrease significantly and, in some cases, tend to zero. Thus, the main influence of the Gaussian pump wave width on the quality of the DRWF is observed in the range of pump wave widths from $b=0,3a$ to $b=2a$.

Conclusion

At the ratio of wave numbers of the second and first pump waves equal to 2 and 0,5, the quality of the doubled wavefront reversal of a signal wave from a point source at six-wave interaction on the Kerr nonlinearity in a waveguide with infinite conducting walls is analyzed.

We demonstrated that the maximum change in the characteristics of the wave with DRWF is observed when changing the width of Gaussian pump waves from $b=0,3a$ to $b=2a$. In this range, at $h=0,5$, a decrease in the widths of the Gaussian pump waves leads both to a decrease in the half-width of the central maximum and to an increase in the contrast of the PSF modulus. At $h=2$, a decrease in the width of the first Gaussian pump wave under the condition of a single-mode second pump wave increases the half-width of the central maximum and weakly affects the contrast of the PSF modulus. The quality of the doubled wavefront reversal of the signal wave from a point source located at the leading edge of the waveguide deteriorates with decreasing width of the first Gaussian pump wave.

References

1. S. M. Karpuk, A. S. Rubanov, and A. L. Tolstik, “Double phase conjugation in quadratic recording of dynamic holograms in resonant media,” *Optika i spektroskopiya*, vol. 80, no. 2, pp. 313–318, 1996, url: https://elibrary.ru/item.asp?id=29196117. (In Russ.)
2. V. V. Ivakhnik, V. I. Nikonov, and M. V. Savelyev, “Double wavefront reversal at six-wave interaction on the thermal nonlinearity,” *Physics of Wave Processes and Radio Systems*, vol. 18, no. 1, pp. 13–17, 2015, url: https://journals.ssau.ru/pwp/article/view/7205. (In Russ.)
3. O. G. Romanov, D. V. Gorbach, and A. L. Tolstik, “Frequency transformation of optical vortices during nondegenerate multi-wave interaction in dye solutions,” *Optika i spektroskopiya*, vol. 108, no. 5, pp. 812–817, 2010, url: https://elib.bsu.by/bitstream/123456789/211782/1/14-A%20Opt-Spectr-2010-rus.pdf. (In Russ.)
4. R. Gupta and R. S. Kaler, “Nonlinear Kerr and intermodal four-wave mixing effect in mode-division multiplexed multimode fiber link,” *Optical Engineering*, vol. 58, no. 3, p. 036108, 2019, doi: https://doi.org/10.1117/1.OE.58.3.036108.
5. H. Zhang et al., “Spatially multiplexed picosecond pulse-train generation in a 6 LP mode fiber based on multiple four-wave mixings,” *Applied Optics*, vol. 58, no. 31, pp. 8570–8576, 2019, doi: https://doi.org/10.1364/AO.58.008570.
6. H. Zhou1 et al., “Six-wave mixing ind,” *Laser Photonics Reviews*, vol. 10, no. 6, pp. 1054–1061, 2016, doi: https://doi.org/10.1002/lpor.201600124.
7. V. V. Ivakhnik and V. I. Nikonov, “Doubled wavefront conjugation for non-degenerate six-photon interaction,” *Optika i spektroskopiya*, vol. 75, no. 2, pp. 385–390, 1993, url: https://elibrary.ru/item.asp?id=37622858. (In Russ.)
8. V. V. Ivakhnik and V. I. Nikonov, “Six-wave interaction with double wavefront reversal on thermal nonlinearity in a medium with a nonlinear absorption coefficient,” *Komp'yuternaya optika*, vol. 41, no. 3, pp. 315–321, 2017, doi: https://doi.org/10.18287/2412-6179-2017-41-3-315-321. (In Russ.)
9. V. V. Ivakhnik, D. R. Kapizov, and V. I. Nikonov, “Six-wave interaction with double wavefront reversal in multimode waveguides with Kerr and thermal nonlinearities,” *Komp'yuternaya optika*, vol. 47, no. 5, pp. 702–709, 2023, doi: https://doi.org/10.18287/2412-6179-CO-1313. (In Russ.)
10. E. S. Voronin, V. M. Petnikova, and V. V. Shuvalov, “Using degenerate parametric processes for wavefront correction (review),” *Kvantovaya elektronika*, vol. 8, no. 5, pp. 917–935, 1981, url: https://www.mathnet.ru/rus/qe/v8/i5/p917. (In Russ.)
11. E. V. Vorob'eva et al., “Point spread function of a four-wave radiation converter in a multimode waveguide with Kerr nonlinearity,” *Physics of Wave Processes and Radio Systems*, vol. 24, no. 1, pp. 15–21, 2021, doi: https://doi.org/10.18469/1810-3189.2021.24.1.15-21. (In Russ.)
12. D. Markuze, *Optical Waveguides*. Moscow: Mir, 1974. (In Russ.)

Information about the Authors

Valery V. Ivakhnik, Doctor of Physical and Mathematical Sciences, professor, head of the Department of Optics and Spectroscopy, Samara National Research University, Samara, Russia.
Research interests: nonlinear optics, dynamic holography.
E-mail: ivakhnik@ssau.ru
SPIN code (eLibrary): 2791-2471
AuthorID (eLibrary): 20229
ResearcherID (WoS): AAH-3584-2019

Darkhan R. Kapizov, 4th year postgraduate of the Department of Optics and Spectroscopy, Samara National Research University, Samara, Russia.
Research interests: nonlinear optics, dynamic holography.
E-mail: darkhankapizov@gmail.com
SPIN code (eLibrary): 6771-2032
AuthorID (eLibrary): 1109458

Vladimir I. Nikonov, Candidate of Physical and Mathematical Sciences, associate professor of the Department of Optics and Spectroscopy, Samara National Research University, Samara, Russia.
Research interests: nonlinear optics, dynamic holography.
E-mail: nikon5919@mail.ru
SPIN code (eLibrary): 1965-3523
AuthorID (eLibrary): 191191
ResearcherID (WoS): S-8516-2016

Физика волновых процессов и радиотехнические системы
2024. Т. 27, № 2. С. 38–44

DOI 10.18469/1810-3189.2024.27.2.38-44
УДК 535.1
Оригинальное исследование

Дата поступления 18 декабря 2023
Дата принятия 19 января 2024
Дата публикации 29 июня 2024

Удвоенное обращение волнового фронта при шестиволновом взаимодействии на керровской нелинейности в волноводе с бесконечно проводящими поверхностями

В.В. Ивахник, Д.Р. Капизов, В.И. Никонов

Самарский национальный исследовательский университет имени академика С.П. Королева
443086, Россия, г. Самара,
Московское шоссе, 34

Аннотация – **Обоснование.** Генерация волны с удвоенным обращенным волновым фронтом в многомодовых волноводах повышает эффективность шестиволновых преобразователей излучения, расширяет возможности их использования в задачах адаптивной оптики, преобразования сложных пространственно неоднородных волн. **Цель.** Проанализировано качество удвоенного обращения волнового фронта при шестиволновом взаимодействии в волноводе с бесконечно проводящими поверхностями с керровской нелинейностью при отношении волновых чисел волн накачки, равном 2 и 0,5, и условии, что одна из волн накачки возбуждает нулевую моду волновода, а распределение амплитуды другой волны накачки на грани волновода описывается гауссовой функцией. **Методы.** Численными методами изучено влияние параметров волн накачки на полуширину и контраст модуля амплитуды объектной волны. В качестве сигнальной использована волна от точечного источника, расположенного на передней грани волновода. **Результаты.** Получены зависимости полуширины и контраста модуля амплитуды объектной волны от соотношения между шириной волновода и шириной гауссовой волны накачки. **Заключение.** Показано, что максимальное изменение характеристик волны с удвоенным обращенным волновым фронтом наблюдается при изменении ширины гауссовых волн накачки в диапазоне от 0,3 до 2 полуширин волновода.

Ключевые слова – шестиволновой преобразователь излучения; удвоенное обращение волнового фронта; керровская нелинейность.

✉ nikon5919@mail.ru (*Никонов Владимир Иванович*)

Список литературы

1. Карпук С.М., Рубанов А.С., Толстик А.Л. Удвоенное фазовое сопряжение при квадратичной записи динамических голограмм в резонансных средах // Оптика и спектроскопия. 1996. Т. 80, № 2. С. 313–318. URL: https://elibrary.ru/item.asp?id=29196117
2. Ивахник В.В., Никонов В.И., Савельев М.В. Удвоенное обращение волнового фронта при шестиволновом взаимодействии на тепловой нелинейности // Физика волновых процессов и радиотехнические системы. 2015. Т. 18, № 1. С. 13–17. URL: https://journals.ssau.ru/pwp/article/view/7205

3. Романов О.Г., Горбач Д.В., Толстик А.Л. Частотное преобразование оптических вихрей при невырожденном многоволновом взаимодействии в растворах красителей // Оптика и спектроскопия. 2010. Т. 108, № 5. С. 812–817. URL: https://elib.bsu.by/bitstream/123456789/211782/1/14-A%20Opt-Spectr-2010-rus.pdf

4. Gupta R., Kaler R.S. Nonlinear Kerr and intermodal four-wave mixing effect in mode-division multiplexed multimode fiber link // Optical Engineering. 2019. Vol. 58, no. 3. P. 036108. DOI: https://doi.org/10.1117/1.OE.58.3.036108

5. Spatially multiplexed picosecond pulse-train generation in a 6 LP mode fiber based on multiple four-wave mixings / H. Zhang [et al.] // Applied Optics. 2019. Vol. 58, no. 31. P. 8570–8576. DOI: https://doi.org/10.1364/AO.58.008570

6. Six-wave mixing induced by free-carrier plasma in silicon nanowire waveguides / H. Zhou1 [et al.] // Laser Photonics Reviews. 2016. Vol. 10, no. 6. P. 1054–1061. DOI: https://doi.org/10.1002/lpor.201600124

7. Ивахник В.В., Никонов В.И. Удвоенное сопряжение волнового фронта при невырожденном шестифотонном взаимодействии // Оптика и спектроскопия. 1993. Т. 75, № 2. С. 385–390. URL: https://elibrary.ru/item.asp?id=37622858

8. Ивахник В.В., Никонов В.И. Шестиволновое взаимодействие с удвоенным обращением волнового фронта на тепловой нелинейности в среде с нелинейным коэффициентом поглощения // Компьютерная оптика. 2017. Т. 41, № 3. С. 315–321. DOI: https://doi.org/10.18287/2412-6179-2017-41-3-315-321

9. Ивахник В.В., Капизов Д.Р., Никонов В.И. Шестиволновое взаимодействие с удвоенным обращением волнового фронта в многомодовых волноводах с керровской, тепловой нелинейностями // Компьютерная оптика. 2023. Т. 47, № 5. С. 702–709. DOI: https://doi.org/10.18287/2412-6179-CO-1313

10. Воронин Э.С., Петникова В.М., Шувалов В.В. Использование вырожденных параметрических процессов для коррекции волновых фронтов (обзор) // Квантовая электроника. 1981. Т. 8, № 5. С. 917–935. URL: https://www.mathnet.ru/rus/qe/v8/i5/p917

11. Функция размытия точки четырехволнового преобразователя излучения в многомодовом волноводе с керровской нелинейностью / Е.В. Воробьева [и др.] // Физика волновых процессов и радиотехнические системы. 2021. Т. 24, № 1. С. 15–21. DOI: https://doi.org/10.18469/1810-3189.2021.24.1.15-21

12. Маркузе Д. Оптические волноводы. М.: Мир, 1974. 576 с.

Информация об авторах

Ивахник Валерий Владимирович, доктор физико-математических наук, профессор, заведующий кафедрой оптики и спектроскопии Самарского национального исследовательского университета имени академика С.П. Королева, г. Самара, Россия.

Область научных интересов: нелинейная оптика, динамическая голография.

E-mail: ivakhnik@ssau.ru

SPIN-код (eLibrary): 2791-2471

AuthorID (eLibrary): 20229

ResearcherID (WoS): AAH-3584-2019

Капизов Дархан Рахметулович, аспирант 4-го года обучения кафедры оптики и спектроскопии Самарского национального исследовательского университета имени академика С.П. Королева, г. Самара, Россия.

Область научных интересов: нелинейная оптика, динамическая голография.

E-mail: darkhankapizov@gmail.com

SPIN-код (eLibrary): 6771-2032

AuthorID (eLibrary): 1109458

Никонов Владимир Иванович, кандидат физико-математических наук, доцент кафедры оптики и спектроскопии Самарского национального исследовательского университета имени академика С.П. Королева.

Область научных интересов: нелинейная оптика, динамическая голография.

E-mail: nikon5919@mail.ru

SPIN-код (eLibrary): 1965-3523

AuthorID (eLibrary): 191191

ResearcherID (WoS): S-8516-2016