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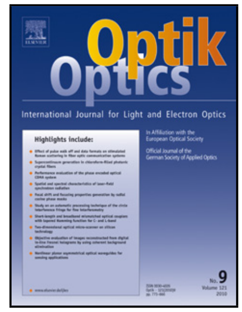

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Nonlinear phase matching in parametric four-wave mixing process of Cs vapor

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Abstract

Phase matching plays an important role on the nonlinear process. The linear phase matching in parametric four-wave mixing (FWM) process of Cs vapor is firstly studied and we find out that linear phase matching can be implemented within narrow range of frequency offsets for involved pumping light. Considering the high pumping power intensity, we innovatively take the influence of nonlinear refractive index to phase matching into account. The relationship between threshold pump intensity and frequency offsets is discovered, and it makes up a complicated curved surface. The threshold has the minimum value when the frequency offset satisfies the condition of $v1+v2=0$. In addition, these simulation results could provide support for further study and pumping parameters selection in FWM process of Cs vapor.

Keywords: atoms physics, phase matching, parametric four-wave mixing

Introduction

In recent years, nonlinear processes in alkali-metal vapor excited by two resonant laser fields have attracted widely interest [1-6], and the phase matching is a great significance to achieve multi-wavelength output. The generation of blue-violet light and mid-infrared light related to pumping laser has been shown to be responsible to parametric four-wave mixing (FWM) and amplified spontaneous emission (ASE), respectively [7-9]. In the process of FWM in Cs vapor, high pumping power intensity is generally essential to obtain promotion of output power, so the nonlinear change of refractive index with intense electric field intensity will have a vital impact on phase matching which plays an important role to enhance conversion efficiency. And investigating the relationship between phase matching and pumping power intensity will be helpful achieving the output of the coherent blue light (CBL) and the coherent mid-IR light (CMIRL) in alkali metal vapor [10]. Hitherto, some researches about the influence of refractive index on phase matching have been made. G. Bjorklund has demonstrated experimentally collinear phase matching in two-photon resonant FWM process of Na vapor and there is not the required phase-matching buffer gas simply by properly choosing the frequencies of the fundamental beams [11]. H. Puell et al. have researched the phase matching condition in third-harmonic generation process of Rb-Xe mixtures in 1976 [12]. Jerzy Krasinski et al. have investigated the angle phase matching in FWM process of Na vapor in 1985 [13]. However, the researches about FWM process in Cs vapor and the influence of nonlinear variation of refractive index on phase matching are extremely absent.

In this paper, we mainly study about the phase matching in FWM process of Cs atoms vapor according to the relations between susceptibility of vapor and refractive index. The ordinary linear phase matching is firstly discussed. And the results illustrate that collinear phase matching is realized within the small ranges of frequency offset. However, the FWM process in Cs vapor generally needs to high power intensity for pumping lasers. Therefore, we innovatively take the influence of nonlinear refractive index to phase matching into account aiming at finding out better pumping way. Through simulation, the relationships among pumping threshold I and frequency offsets are discovered and analyzed on the condition of satisfying phase matching. It independently makes up complex curved surfaces in special regions of frequency offsets, and minimum values of pumping power intensity could be acquired according to actual pumping situations. And these simulation works provide useful information for further understanding on phase matching with the participation of nonlinear refractive index and selection of pumping parameters.

Theoretical model

The process of FWM in Cs metal vapor is illustrated in Fig. 1. The Cs energy levels $6S_{1/2}$, $6P_{3/2}$, $7P_{3/2}$ and $6D_{5/2}$ which are representatively involved in Cs vapor are respectively replaced by the symbols of |a>, |b>, |c> and |d>. The FWM process interested in Cs vapor is different from common-sense FWM, which has only two resonant lasers with different frequency vba and vcb as involved parametric light. The third crucial component of this nonlinear process is provided by the ASE between the states of |c> and |d>, and the output is the generation of violet-blue light with frequency vda. This way constitutes the two-photon absorption FWM process in Cs vapor, and we mainly discuss this situation in the text.

Same with normal FWM, the process of FWM in Cs metal vapor similarly meets the phase matching conditions. The collinear phase matching conditions are need to simultaneously satisfy $\nu_{ba}+\nu_{cb}=\nu_{cd}+\nu_{da}$ and $n_{ba}\nu_{ba}+n_{cb}\nu_{cb}=n_{cd}\nu_{cd}+n_{da}\nu_{da}$. The ν_{ba}, ν_{cb}, ν_{cd} and ν_{da} are the frequency of incident laser and generated light, respectively. The following focus on the solution of the refractive index.

The linear refractive index n_0 is derived as [14]

$$n_0(\nu_i)=1+\frac{\mathrm{Re}(\chi^{(1)}(\nu_i))}{2}, \tag{1}$$

And the linear susceptibility of transition between state |b> and |a> is expressed as

$$\chi^{(1)}(\nu_{ba})=\frac{N}{\varepsilon_0 h}\sum_b \rho_{aa}^0\left(\frac{\mu_{ab}\mu_{ba}}{\nu'_{ba}-\nu_{ba}-i\Gamma_{ba}}+\frac{\mu_{ab}\mu_{ba}}{\nu'_{ba}+\nu_{ba}+i\Gamma_{ba}}\right), \tag{2}$$

Where N is the number of Cs atoms per unit volume, and $\nu'_{ba}=(E_b-E_a)/h$ which represents the transition frequency from state |b> to |a>. The ν_{ba} is the frequency of first pumping laser, and Γ_{ba} is the phase relaxation rate. Where $\rho_{aa}^0=(2J_a+1)^{-1}$ is the occupation probability of atomic state |a> and ε_0 is permittivity of vacuum. We assume that the incident pumping laser fields are linearly polarized in the z direction. The μ_{ab} is corresponding dipole moment matrix element of the transition. The other three linear susceptibilities can be obtained by substituting the subscript with relative states.

Generally, the regulation precision of center frequency of pumping laser is comparatively low for special wavelength using in FWM of Cs vapor, so the frequency difference between center frequency of pumping lasers and transition frequency is fairly large that may be about 1×10^{10}Hz corresponding to linewidth with 0.03nm. Because of the reasons, the external-cavity diode laser (ECDL) is one way to solve the problem. However, it usually has too small power to provide enough light intensity which limits the range of application. Therefore, the lasers normally used in FWM process of Cs vapor need to high power intensity. And the influences of nonlinear process for two pumping lasers to nonlinear refractive index must be taken into account in this condition. The impact of second pumping laser (with frequency ν_{cb}) can be ignored owing to the occupation probability of atomic state |b> is far less than that of state |a>. The third-order susceptibility of first pumping laser is derived as [14]

$$\chi^{(3)}(\nu_{ba},\nu_{ba},-\nu_{ba})=\frac{N}{6\varepsilon_0 h^3}\sum_{a,b,c}\rho_{aa}^0\frac{\mu_{ab}^2\mu_{bc}^2}{(\nu'_{ba}-\nu_{ba}-i\Gamma_{ba})^2(\nu'_{ca}-2\nu_{ca}-i\Gamma_{ca})}, \tag{3}$$

Where $\nu'_{ca}=(E_c-E_a)/h$. Taking the condition that intensity of generated light is extremely low comparing with pumping laser into account [1,15], the influence of FWM causing by two resonant lasers to nonlinear refractive index $n_{\text{non-da}}$ is mainly considered. The third-order susceptibility of generated light (with frequency ν_{da}) is given by [14]

$$\chi^{(3)}(\nu_{ba},\nu_{cb},-\nu_{cd}) = \frac{N}{6\varepsilon_0 h^3}\sum_{a,b,c,d}\rho^0_{aa} \times \frac{\mu_{ab}\mu_{bc}\mu_{cd}\mu_{da}}{(\nu'_{ba}-\nu_{ba}-i\Gamma_{ba})(\nu'_{ca}-\nu_{ba}-\nu_{cb}-i\Gamma_{ca})(\nu'_{da}-\nu_{ba}-\nu_{cb}+\nu_{cd}-i\Gamma_{da})}, \quad (4)$$

The nonlinear refractive index for two resonant lasers and generated light is given by [16]

$$n_{non} = \frac{3\mathrm{Re}(\chi^{(3)})}{4\varepsilon_0 n_0^2 c} I, \quad (5)$$

Where I is the light intensity and c is the speed of light. The pumping intensity for $n_{\text{non-da}}$ in Eq. (5) is

$$I = \sqrt{I_1 I_2}, \quad (6)$$

Where I_1 and I_2 are the laser power intensity for ν_{ba} and ν_{cb}, respectively.

The total refractive index is the summation of linear and nonlinear refractive index

$$n_{tol}(\nu_i) = n_0(\nu_i) + n_{non}(\nu_i), \quad (7)$$

Considering the relationship of energy states $\nu'_{ba}+\nu'_{cb}=\nu'_{cd}+\nu'_{da}$, the collinear phase matching conditions are simplified as

$$\begin{aligned} &\nu_1+\nu_2=\nu_3+\nu_4 \\ &\nu_{ba}\left(\frac{\mathrm{Re}(\chi^{(1)}(\nu_{ba}))}{2}+n_{non}(\nu_{ba})\right)+\nu_{cb}\left(\frac{\mathrm{Re}(\chi^{(1)}(\nu_{cb}))}{2}+n_{non}(\nu_{cb})\right) \\ &=\nu_{cd}\left(\frac{\mathrm{Re}(\chi^{(1)}(\nu_{cd}))}{2}+n_{non}(\nu_{cd})\right)+\nu_{da}\left(\frac{\mathrm{Re}(\chi^{(1)}(\nu_{da}))}{2}+n_{non}(\nu_{da})\right) \end{aligned}, \quad (8)$$

Where the $\nu_1=\nu'_{ba}-\nu_{ba}$, $\nu_2=\nu'_{cb}-\nu_{cb}$, $\nu_3=\nu'_{cd}-\nu_{cd}$ and $\nu_4=\nu'_{da}-\nu_{da}$. The $n_{non}(\nu_{cb})$ and $n_{non}(\nu_{cd})$ can be neglected based on the foregoing analysis. The refractive indexes (linear and nonlinear) for ν_{ba} and ν_{da} contain both positive and negative values, so it needs to search for the certain regions about ν_1, ν_2 and ν_4 to achieve nonlinear phaser matching. And four regions are identified based on Eq. (8) when the power intensity for ν_{ba} is less than 1×10^{11}W/m^2. These are given by

$$\begin{aligned} &(1)\ \nu_1>0, \nu_1+\nu_2>0, \nu_4<0 \\ &(2)\ \nu_1<0, \nu_1+\nu_2>0, \nu_4<0 \\ &(3)\ \nu_1>0, \nu_1+\nu_2<0, \nu_4>0 \\ &(4)\ \nu_1<0, \nu_1+\nu_2<0, \nu_4>0 \end{aligned}, \quad (9)$$

Equations (9-1) and (9-4), (9-2) and (9-3) are symmetric about origin. Therefore, the distribution of condition (9-1) and (9-2) can be taken as representations of nonlinear phase matching.

Result and Discussion

For Cs vapor, the phase relaxation rate Γmn is mainly relevant to the state lifetime and the Doppler broaden effect. The states lifetime is the scale of dozens to hundred nanoseconds, whose magnitude of Γmn is far less than that causing by Doppler effect. The formula can be expressed as [17]

$$\Gamma_{mn} = 2\nu_{mn}\left(\frac{2k_b T}{mc^2}\ln 2\right)^{1/2}, \quad (10)$$

Where ν_{mn} is the relative transition frequency from m state to n state. The k_b is the Boltzmann constant, the temperature T in Kelvin. The m is the Cs atomic mass. Moreover, the number of Cs atoms also varies with the vapor temperature, which can achieve by the relationship between the pressure and temperature of Cs.

The four residual linear refractive indexes versus frequency offset involved in the process of FWM are shown in Fig. 2, when temperature of Cs vapor is set to 400K. The population density of Cs atoms is compensated without considering the influence of nonlinear index.

However, the phase relaxation rate Γ_{mn} which increases with temperature contributes to the decrease of residual linear refractive index, and it directly reflects the width between peak and valley of residual linear refractive index. It can be seen in Fig. 2 that the residual refractive indexes for v_{ba} and v_{da} are far larger than that of v_{cb} and $\underline{v}_{cd}$. Therefore, the major influencing factors of phase matching are the transition frequency offsets for v_{ba} and v_{da}, and two terms of $n_{cb}v_{cb}$ and $n_{cd}v_{cd}$ in linear phase matching can be neglected. To meet the phase matching, the frequency offset for v_1 should be greater than 9×10^{10} Hz for forward deviation, and the minimum frequency offset for v_4 is 0.3×10^{10}Hz calculating according to the data in Fig. 2. For the FWM process in Cs vapor with single-wavelength laser excitation (v_{ba}=v_{cb}), the large v_1 frequency offset is inevitable, which will destroy the phase matching condition and restrict the conversion ratio from v_{ba} and v_{cb} to v_{cd} and v_{da}. One way reducing the impact of v_1 frequency offset on phase matching is the angular phase matching, and the situation is similar to the discussion in Ref. 13.

As previously mentioned, the influence of nonlinear process on refractive index should be taken into account, which directly affects the phase matching in Cs vapor at high pumping power intensity. The third order nonlinear effect on refractive index of n_{cb}, n_{cd} and the Kerr-effect on n_{da} are overlooked comparing with n_{ba} and n_{da}. The nonlinear refractive index for v_{ba} ($n_{non\text{-}ba}$) is the function of v_1, Γ_{ba} and I_1, and nonlinear refractive index for v_{da} ($n_{non\text{-}da}$) is the function of $f(v_1, v_2, v_4, \Gamma_{mn}, I_1, I_2)$. It can be seen in Fig. 3 that the $n_{non\text{-}ba}$ causing by Kerr effect is closely interrelated with Γ_{ba} which decides on the full width at half maximum (FWHM) for the product of $n_{non\text{-}ba}$ and v_{ba}. The product is proportional to the laser power intensity for v_{ba}, and it has little impact on the area far from center frequency. Comparing with residual linear refractive index $n_{r\text{-}ba}$ in Fig. 2(a), whose product of residual linear refractive index $n_{r\text{-}ba}$ and v_{ba} is about magnitude of 10^{11}, the threshold of reaching same magnitude is roughly 1×10^{11}W/m^2.

We only take the condition of v_1>0 into account owing to the symmetry of $n_{non\text{-}ba}$ and $n_{non\text{-}da}$ for corresponding frequency offset. The parameters for nonlinear phase matching are copious such as v_1, v_2, v_4, Γ_{mn}, I, and it's impossible to discuss the relationship of each other. We take parameters v_1, v_2 and v_4 as independent variables respectively, and the I can be obtained when the nonlinear phase matching is satisfied. The pumping intensity I represents the minimum pumping intensity that can be seen as the threshold intensity for the FWM in Cs vapor under present condition. The Fig. 4 shows that required pumping light intensity I has an intimately association with v_1, v_2 and v_4 with the condition of v_1+v_2>0 and v_4<0. From Fig. 4(a), we can see that the I rapidly increase with v_1 and v_2, and there exists the special value of v_1 for certain v_2. The increasing rate of I changes from high to low when the frequency offset of v_1 is before and after special value of v_1. And there is the same condition as v_1 varies for certain v_4 in Fig. 4(b). Different with Fig. 4(a), the I in Fig. 4(b) has minimal value which is the function of v_1, v_2 and Γ_{mn} as v_4 changes. However, an important point to note is that the value of I approaches to infinity when v_4 is almost near zero, so it is impossible to achieve the output of narrow linewidth of v_{da} under the situation of nonlinear phase matching.

Another condition of v_1+v_2<0 and v_4>0 for v_1>0 is shown in Fig. 5. The range of parameter v_2 in Fig. 5(a) is set up from -7.5×10^{10}Hz to -11×10^{10}Hz for realization of v_1+v_2<0. The threshold pumping intensity I is at rapid growth firstly and then slow decrease with v_1 when the frequency offset v_2 is treated as fixed value in Fig. 5(a), and the I always increase with v_2 in negative direction. This is extremely engrossing appearance. The curved surface of Fig. 5(b) is like to asymmetric saddle shape from horizontal perspective of v_4. It can be seen from Fig. 5(b) that the maximum of I been emergence in both ends of value for v_4 and for v_1 is in the vicinity of 2.6×10^9Hz. It is not difficult to discovery in Fig. 5(b) that the threshold I in the area close to v_1+v_2=0 is far less than other domain, so it provides significant thought for us about how to reduce the pumping light intensity based on keeping conversion efficiency in Cs vapor.

The threshold I is the function of v_1, v_2 and v_4 when the temperature remains constant. The threshold I is approximately 1×10^{10}W/m^2 when frequency offsets of v_1 and v_4 are respectively about 1.5×10^{10}Hz and -1.1×10^{10}Hz with v_2 of 2×10^{10}Hz in Fig. 4(a). The simulation outcome is close to the experimental result by using the relative parameters of frequency offset [18], which can indirectly reflect the rationality of simulation. In addition, the available literatures about the pumping threshold of Cs vapor are the condition of pumping with single-wavelength laser, which also could be used to validate the model with $\nu_{ba}=\nu_{cb}$. And the frequency offset of $\nu_1+\nu_2$ is generally neglected comparing with ν_1 which mainly represent the frequency offset between pumping meddle virtual level and $6P_{1/2,3/2}$ levels. Therefore, the three-dimensional figures for Fig. 3, 4 and 5 become two-dimensional ones. The ν_1 are respectively about 3.5×10^{13}Hz and 1.3×10^{13}Hz with pumped upper level of $6D_{3/2}$ (corresponding to frequency offset of virtual level with $6P_{1/2}$ levels and of virtual level with $6P_{3/2}$ levels, respectively). The simulation result based on our model is about 0.97×10^{8}W/m^2 when the value of v1+v2 is set as 1×10^{6}Hz according to the reference. This value agrees well with the experimental data 1.5×10^{8}W/m^2 [19]. The pumping threshold intensity with single-wavelength laser of Cs vapor is approximately 2.26×10^{10}W/m^2 when the upper level is $7D_{5/2}$ [15]. By substituting the corresponding parameters in the paper [15] into our model, the value is 3.81×10^{10}W/m^2 which is in good agreement with experimental data.

Temperature of Cs vapor is another unavoidable influence factor to nonlinear phase matching. The impacts of temperature concentrate on the Cs atoms density and phase relaxation rate Γ_{mn}, and the influence of Cs atoms density on the nonlinear phase matching could be eliminated according to Eq. (8). Therefore, the change of temperature has effects on the Γ_{mn} which leads to transformation of curved surface of I in Fig. 4 and Fig. 5. The Γ_{mn} slowly increase with temperature from Eq. (10) and it has a limited effect on nonlinear phase matching by changing the temperature. However, it is efficient to achieve phase matching by adjusting temperature of Cs vapor when the frequency offsets for ν_1, ν_2 and ν_4 are in the same magnitude.

Conclusion

In this study, we point out the linear phase matching can only be implemented on the small scale of frequency offsets for v1 and v2, which is difficult to realize in practice. Therefore, the influence of nonlinear variation of refractive index is innovatively taken into account considering the pumping intensity. Four areas for nonlinear phase matching are discovered based on the symmetry of nonlinear refractive index. And simulation works show that pumping threshold I has a close relationship with frequency offsets of v1, v2 and v4. The pumping intensity can be effectively decreased when the frequency offset satisfies v1+v2=0. The simulation results agree well with available experimental data. More significantly, the researches provide important support for counterpoising the pumping parameters selection and provide enlightenment in further study. The approach is also suited for similar phase matching process in other alkali metal vapor such as Na, K and Rb.

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References

[1] J. T. Schultz, S. Abend, D. Döring, J. E. Debs, P. A. Altin, J.D. White, N.P. Robins, and J. D. Close, "Coherent 455 nm beam production in a cesium vapor," Opt. Lett. 34(15), 2321-2323 (2009).

[2] E. Brekke and L. Alderson, "Parametric four-wave mixing using a single cw laser," Opt. Lett. 38(12), 2147-2149 (2013).

[3] Y. F. Hsiao, P. J. Tsai, H. S. Chen, S. X. Lin and Y. C. Chen, Phys. Rev. Lett. 120(18), (2018).

[4] A. M. Akulshin, D. Budker, and R. J.Mclean "Parametric wave mixing enhanced by velocity insensitive two-photon excitation in Rb vapour," J. Opt. Soc. Am. B 34(5), 1016-1022 (2017).
[5] J. F. Sell, B. D. Depaola, R. J. Knize and M. A. Gearba, "Collimated blue and infrared beams generated by two-photon excitation in Rb vapor," Opt. Lett. 39(3), 528-531 (2014).
[6] L. Amy, L. Lenci, S. Villalba, H. Failache and A. Lezama, "Two-photon excitation of rubidium atoms inside porous glass," Phys. Rev. A 96(4), (2017).
[7] S. M. Hamadani, J. A. D. Stockdale and R. N. Compton, "Two-Photon Resonant Four-Wave Mixing And Multiphoton Ionization Of Cesium In A Heat Pipe Oven," Phys. Rev. A 34(3), 1938-1943 (1986).
[8] A. M. Akulshin, R. J. Mclean, A. I. Sidorov and P. Hannaford, "Collimated blue light generated by four-wave mixing in Rb vapour," Opt. Express 17(25), 22861 (2009).
[9] T. Efthimiopoulos, M. E. Movsessian, M. Katharakis and N. Merlemis, "Cascade emission and four-wave mixing parametric processes in potassium," J. Appl. Phys. 80(2), 639-643 (1996).
[10] Y. Sebbag, Y. Barash, and U. Levy, "Generation of coherent mid-IR light by parametric four-wave mixing in alkali vapor," Opt. Lett. 44(4), 971-974 (2019).
[11] G. C. Bjorklund, J. E. Bjorkholm, P. F. Liao and R. H. Storz, "Phase matching of two‐photon resonant 4‐wave mixing processes in alkali metal vapors," Appl. Phys. Lett. 29(11), 729-732 (1976).
[12] H. Puell and C. R. Vidal, "Third-harmonic generation of mode-locked Nd:glass laser pulses in phase-matched Rb-Xe mixtures," Phys. Rev. A 14(6), 2240-2257 (1976).
[13] J. Krasinski, D. J. Gauthier, M. S. Malcuit and R. W. Boyd, "Two-photon conical emission," Opt. Commun. 54(4), 241-245 (1985).
[14] S.-X. Shi, G.-F. Chen, W. Zhao and J.-F. Liu, "Nonlinear Optica," Chap. 5, second edition (2012, Xidian University).
[15] B.-D. Gai, R. Cao, X.-S. Xia, S. Hu, J.-B. Liu, J.-W. Guo, Y.-N. T, W.-F. Liu, Y.-Q. Jin and F.-T. Sang, "Modulation of a double-line frequency up-conversion process in cesium vapor," Appl. Phys. B: Lasers Opt. 122(6), 165 (2016).
[16] N. T. Anh, L. V. Doai and N. H. Bang, "Manipulating multi-frequency light in a five-level cascade-type atomic medium associated with giant self-Kerr nonlinearity," J. Opt. Soc. Am. B 35(6), 1233-1239 (2018).
[17] T. S. William, Chap. 4, "Laser Fundamentals," second edition (2004, Cambridge University).
[18] C. V. Sulham, G. A. Pitz and G. P. Perram, "Blue and infrared stimulated emission from alkali vapors pumped through two-photon absorption," Appl. Phys. B: Lasers Opt. 101(1-2), 57-63 (2010).
[19] N. D. Haluska, G. P. Perram and C. A. Rice, "Efficient non-linear two-photon effects from the Cesium 6D manifold," Nonlinear Frequency Generation and Conversion: Materials and Devices XVII. International Society for Optics and Photonics. 10516, 1051606 (2018).

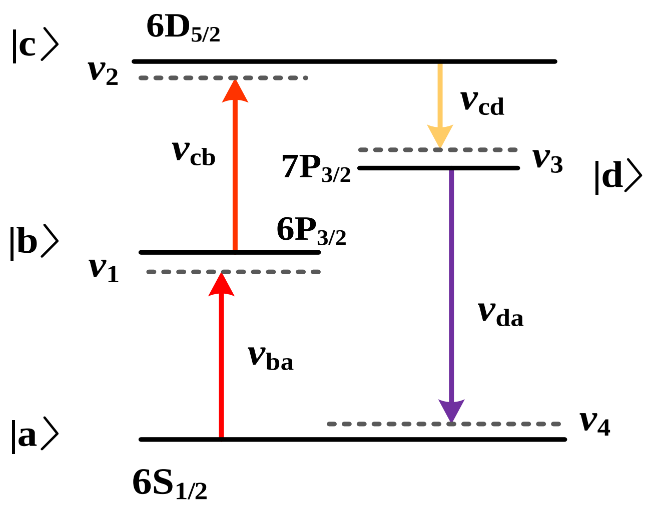


Fig. 1 The energy levels of Cs atom and FWM process in Cs vapor

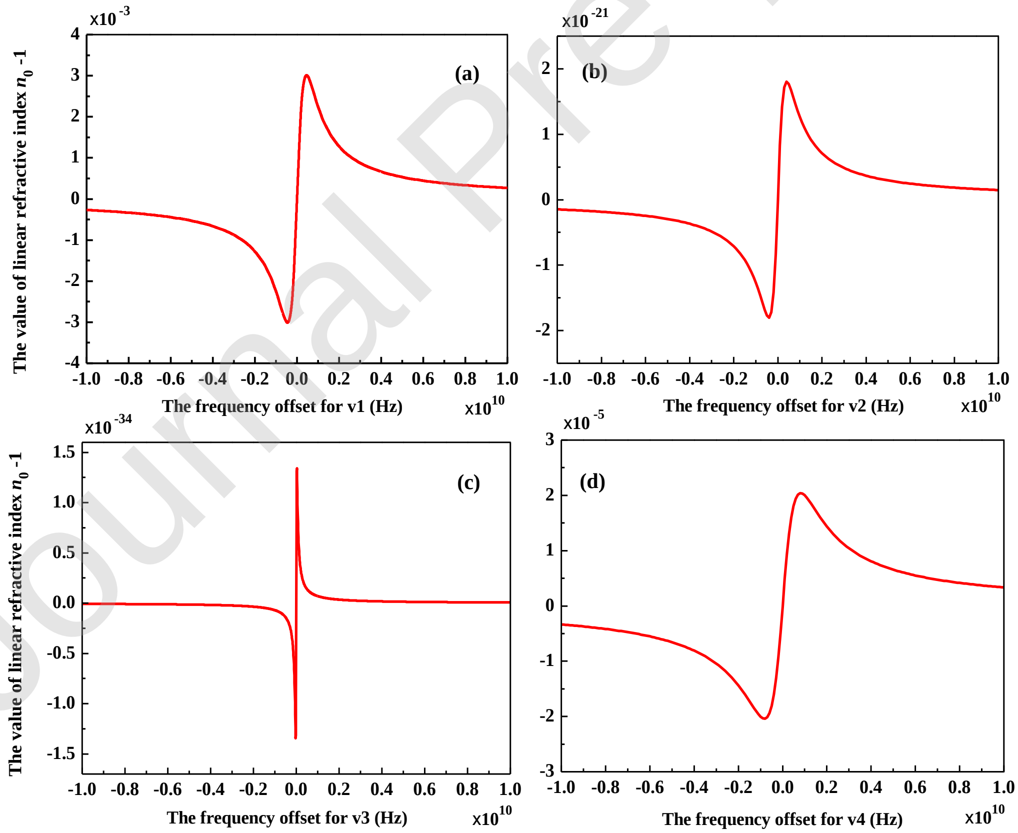


Fig. 2 The four residual linear refractive indexes (n_0-1) versus frequency offset when the temperature is 400K.

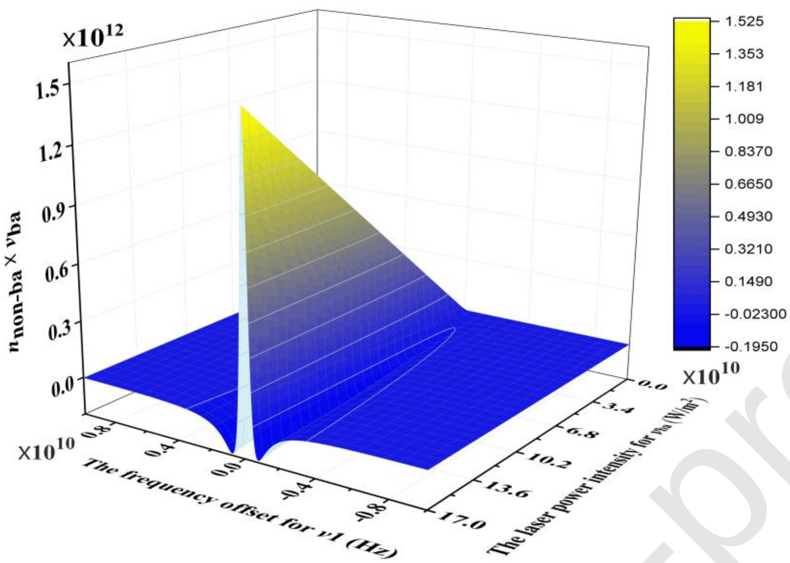
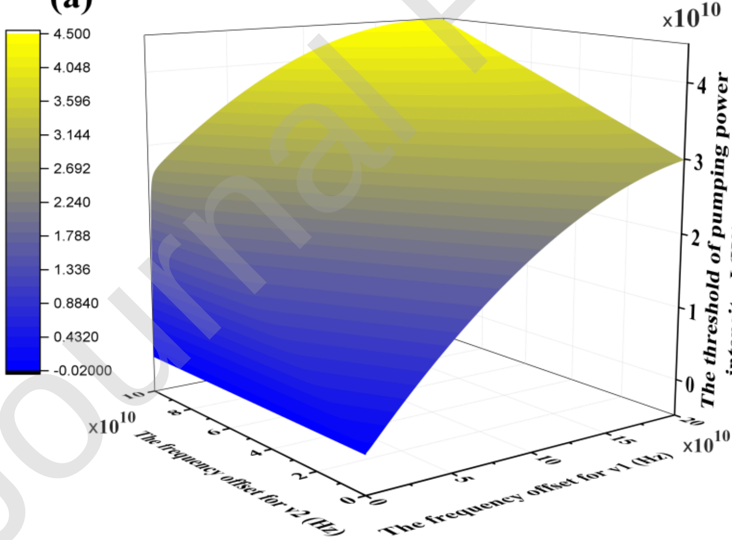


Fig. 3 The product of nonlinear refractive index $n_{\text{non-ba}}$ and v_{ba} versus the frequency offset for v_1 and laser power intensity for v_{ba}. The temperature of Cs vapor is 400K corresponding to Γ_{ba} with 4.3×10^8Hz.

(a)



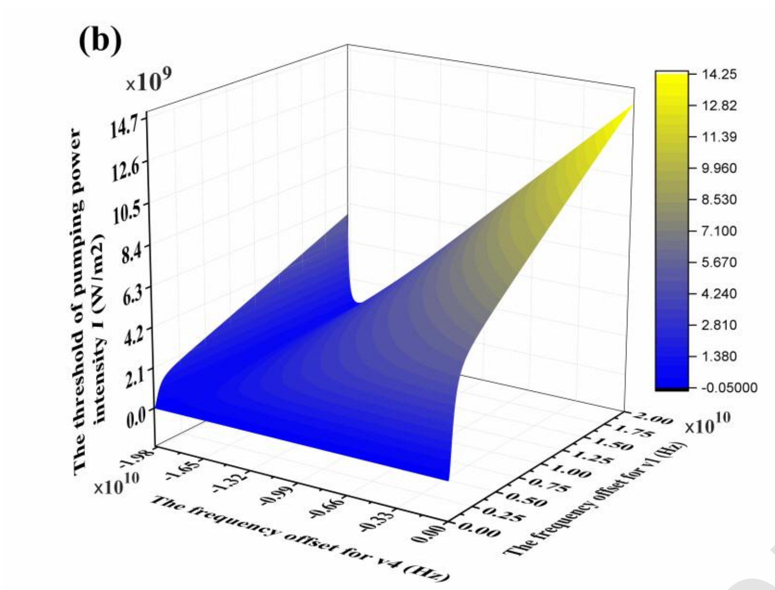
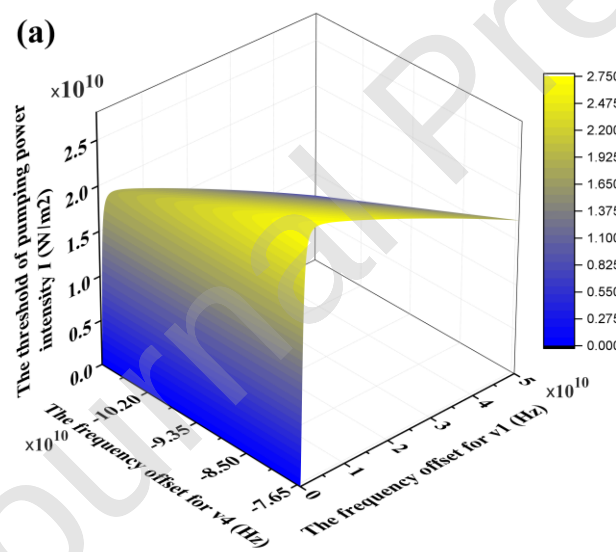


Fig. 4 The threshold of pumping intensity *I* versus frequency offsets of v_1, v_2 and v_4 for condition of $v_1+v_2>0$ and $v_4<0$, respectively when temperature of Cs vapor is 400K. (a) The v_4 is set up as -1.1×10^{10}Hz; (b) The v_2 is set up as 1.1×10^{10}Hz.



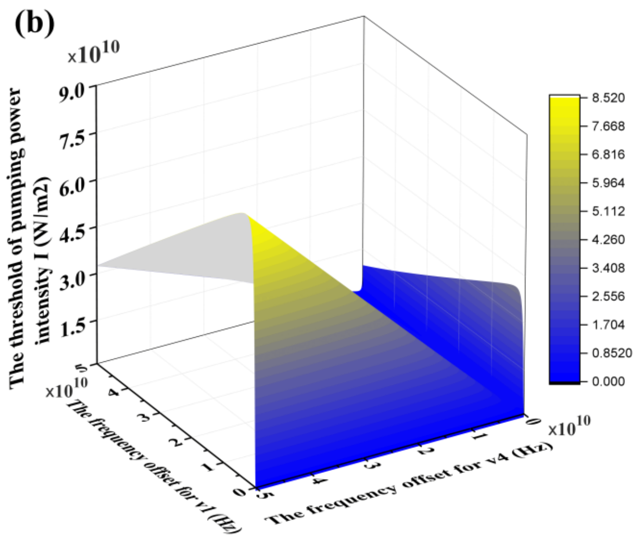


Fig. 5 The threshold of pumping intensity I versus frequency offsets of v_1, v_2 and v_4 for condition of $v_1+v_2<0$ and $v_4>0$, respectively when temperature of Cs vapor is 400K. (a) The v_4 is set up as 1×10^{10}Hz ;(b) The v_2 is set up as -2.1×10^{11}Hz.