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色散缓变光纤中五阶非线性调制不稳定性

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摘要: 在三五阶非线性共存时, 研究了有损耗单模光纤中基于两光波交叉相位调制的不稳定条件和增益谱。在色散缓变光纤正色散区, 分析了五阶非线性系数、色散纵向变化参量以及两扰动的频率大小关系对交叉相位调制不稳定增益谱的影响。结果表明, 在五阶非线性下, 色散的纵向渐减仍有利于展宽调制不稳定增益谱; 正五阶非线性可使增益谱的谱宽和谱峰值增大, 并使谱峰位置远离主波频率, 负五阶非线性的作用则相反; 两扰动频率大小关系不同, 色散纵向参量的变化对增益谱的谱峰大小和位置的影响也不同, 五阶非线性对交叉相位调制不稳定性的加强或抑制程度也不同。

关键词: 非线性光学; 交叉相位调制不稳定性; 色散缓变光纤; 增益谱
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Modulation instability in the decreasing dispersion fibers with quintic nonlinearity

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Abstract In case of co-existence of cubic and quintic nonlinearity, the condition and power gain spectra of modulation instability induced by the cross-phase modulation for two optical waves in loss, single-mode optical fibers are studied. In the normal dispersion region of the decreasing dispersion fibers, the effects of the quintic nonlinear coefficients, the dispersion longitudinal varying parameters, and the size relation of the two perturbation frequencies on the power gain spectra of modulation instability are analyzed in detail. The results indicate that, in case of quintic nonlinearity, the longitudinal decreasing of dispersion is still benefit to broaden the gain spectra of modulation instability. The positive quintic nonlinearity will make the width and the peak value of the gain spectra larger, and make the position of peak value be far away from the frequency of the main wave, while the negative quintic nonlinearity will do the opposite. If the size relation of the two perturbation frequencies is different, the dispersion longitudinal varying parameters will influence the position and value of the spectrum peak in different ways, and the quintic nonlinearity will intensify or suppress the modulation instability to different degrees.

Key words nonlinear optics; modulation instability induced by cross-phase modulation; decreasing dispersion optical fibers; gain spectra

引 言

光纤中色散和非线性效应的相互作用在一定条件下将导致弱的扰动指数式增长, 从而使稳态传输的光变得不稳定的现象称为调制不稳定性[1]。调制不稳定可用于产生重复频率可调的超短光脉冲串[1,2]、制成调制不稳定激光器[2]以及产生时间光孤子[1]。同时调制不稳定也是影响 DWDM 光通信系统性能的一个重要因素[1,3]。因此, 调制不稳定的研究一直倍受人们青睐。近几年的研究表明, 色散缓变光纤可用于产生超宽带连续谱[4], 也比普通光纤更易于产生调制不稳定[5]。

三阶非线性折射率存在时普通光纤和色散缓变光纤中的自相位调制不稳定[1,5,6]和交叉相位调制不稳定[7~9]均已得到广泛研究。但是, 当入射光较强, 或者在诸如半导体掺杂的玻璃、有机聚合物等具有相对较高非线性光学系数的材料中, 即使是中等光强的光入射, 也需考虑五阶甚至更高阶非线性折射率影响[10]。所以, 近几年来, 人们对这种三五阶非线性同时存在时的光孤子[11,12]传输特性以及调制不稳定性[13,14]产生了极大的兴趣。HONG 和 REN 等人在考虑光纤中高阶色散的情况下对三五阶非线性同时存在时普通光纤中的自相位调制不稳定条件及增益谱作了研究[13,14]。但对于三五阶非线性同时存在时色散缓变光纤中双光

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束的交叉相位调制不稳定性则未见报道。

在三五阶非线性共存时,作者研究了有损耗单模色散缓变光纤正色散区的交叉相位调制不稳定条件和增益谱。详细分析了五阶非线性系数、色散纵向变化参量以及两扰动的频率大小关系对交叉相位调制不稳定增益谱的影响。结果表明,在五阶非线性下,色散的纵向缓变仍然有利于展宽调制不稳定增益谱;而正五阶非线性可使增益谱的谱宽和谱峰值增大,并使谱峰位置远离主波频率,负五阶非线性的作用则相反;两扰动频率大小关系不同,色散纵向参量的变化对增益谱的谱峰大小和位置的影响也不同,五阶非线性对交叉相位调制不稳定性的加强和抑制程度也不同。

1 数学模型及理论分析

采用类似文献[1]中的方法可推得基于两光波交叉相位调制的五阶感应电极化强度的幅度为:

$$p^{(5)}(\omega_j) = \frac{5}{8}\varepsilon_0\chi^{(5)}(|E_j|^4 + 3|E_{3-j}|^4 + 6|E_j|^2|E_{3-j}|^2)E_j,\ (j = 1, 2) \tag{1}$$

式中, ω_j 和 E_j 分别是两光波的载频和电场振幅, $\chi^{(5)} = \chi^{(5)}_{xxxxxx}$ 是 x 轴向的五阶电极化率。将五阶感应极化强度的幅度与三阶及线性部分的幅度写在一起,则有:

$$p(\omega_j) = p(\omega_j) + p^{(3)}(\omega_j) + p^{5}(\omega_j) = \varepsilon_0\varepsilon_j E_j \tag{2}$$

在光纤中,(2)式中的相对电容率 ε_j 为:

$$\varepsilon_j = \varepsilon_j^{(1)} + \varepsilon_j^{(3)} + \varepsilon_j^{(5)} = [n_j^{(1)} + \Delta n_j^{(3)} + \Delta n_j^{(5)}]^2 \tag{3}$$

考虑到(1)式~(3)式及 $\Delta n_j = \Delta n_j^{(3)} + \Delta n_j^{(5)} \ll n_j^{(1)}$,则有:

$$\Delta n_j = \frac{\varepsilon_j^{(3)}}{2n_j} + \frac{\varepsilon_j^{(5)}}{2n_j} = \Delta n_j^{(3)} + \Delta n_j^{(5)} \tag{4}$$

式中,三阶和五阶非线性折射率 $\Delta n_j^{(3)}$ [1]和 $\Delta n_j^{(5)}$ 分别为:

$$\begin{cases} \Delta n_j^{(3)} = \dfrac{3}{8n_j^{(1)}}\mathrm{Re}[\chi^{(3)}](|E_j|^2 + 2|E_{3-j}|^2) + \dfrac{i\alpha_j}{2k_{0j}} \\ \Delta n_j^{(5)} = \dfrac{5}{16n_j^{(1)}}\mathrm{Re}[\chi^{(5)}](|E_j|^4 + 3|E_{3-j}|^4 + 6|E_j|^2|E_{3-j}|^2) \end{cases} \tag{5}$$

式中, $\chi^{(3)} = \chi^{(3)}_{xxxx}$ 为 x 轴向的三阶电极化率, α_j 为损耗系数, k_{0j} 为载频波数。由(5)式可见,三五阶非线性折射率相同的项都包括自身光强引起的部分(与自相位调制有关)和其它光波光强引起的部分(与交叉相位调制有关),不同的是,五阶非线性折射率中还包括两光波共同作用引起的折射率变化(也与交叉相位调制有关)。

再按照类似文献[1]中的推导方法,可以得到两光波慢变振幅满足的耦合非线性方程组为:

$$\frac{\partial A_j}{\partial z} + \frac{1}{v_{gj}}\frac{\partial A_j}{\partial t} + \frac{i}{2}\beta_{2j}\frac{\partial^2 A_j}{\partial t^2} + \frac{\alpha_j}{2}A_j = i\gamma_{1j}(|A_j|^2 + 2|A_{3-j}|^2) + i\gamma_{2j}(|A_j|^4 + 3|A_{3-j}|^4 + 6|A_j|^2|A_{3-j}|^2) \tag{6}$$

式中, A_j 表示两光波的慢变振幅, v_{gj} 是两光波的群速度, β_{2j} 是两光波的二阶群速度色散系数,对色散缓变光纤, $\beta_{2j} = \beta_{2j}(0)\exp(-\mu_j z)$, μ_j 为光纤色散纵向变化参量, γ_{1j} 是两光波的三阶非线性系数, γ_{2j} 是两光波的五阶非线性系数。

令(6)式的时间微分项为0,可解得稳态解为:

$$\overline{A}_j = \sqrt{P_j}\exp(-\frac{1}{2}\alpha_j z)\exp(i\phi_j) \tag{7}$$

式中, P_j 表示两光波的入纤光功率,将(7)式代入稳态的方程组可得非线性相移 ϕ_j 为:

$$\phi_j = \gamma_{1j}P_j[1 - \exp(-\alpha_j z)]/\alpha_j + 2\gamma_{1j}P_{3-j}[1 - \exp(-\alpha_{3-j}z)]/\alpha_{3-j} + \gamma_{2j}P_j^2[1 - \exp(-2\alpha_j z)]/(2\alpha_j) + 3\gamma_{2j}P_{3-j}^2[1 - \exp(-2\alpha_{3-j}z)]/(2\alpha_{3-j}) + 6\gamma_{2j}P_jP_{3-j}[1 - \exp(-\alpha_j z)\exp(-\alpha_{3-j})]/(\alpha_j + \alpha_{3-j}) \tag{8}$$

在(7)式中加入微扰 a_j ($|a_j|^2 \ll P_j$)以检验解的稳定性:

$$A_j = (\sqrt{P_j} + a_j)\exp(-\frac{1}{2}\alpha_j z)\exp(i\phi_j) \tag{9}$$

将(8)式、(9)式代入(6)式并线性化后可得到微扰 a_j 满足的方程组:

$$\frac{\partial a_j}{\partial z} + \frac{1}{v_{gj}}\frac{\partial a_j}{\partial t} + \frac{i}{2}\beta_{2j}(0)\exp(-u_j z)\frac{\partial^2 a_j}{\partial t^2} = i\gamma_{1j}P_j \times \exp(-\alpha_j z)(a_j + a_j^*) + i2\gamma_{1j}\sqrt{P_1P_2}\exp(-\alpha_{3-j}z)(a_{3-j} + a_{3-j}^*) + i2\gamma_{2j}P_j\exp(-\alpha_j z)[P_j\exp(-\alpha_j z) + 3P_{3-j} \times \exp(-\alpha_{3-j}z)](a_j + a_j^*) + i6\gamma_{2j}\sqrt{P_1P_2}\exp(-\alpha_{3-j}z) \times [P_j\exp(-\alpha_j z) + P_{3-j}\exp(-\alpha_{3-j}z)](a_{3-j} + a_{3-j}^*) \tag{10}$$

当 $\gamma_{2j} = 0$ 以及 $\alpha_j = 0$ 时,上式与文献[1]中的情形一致。

2 不稳定条件及增益谱分析

根据(10)式并采用文献[6]~文献[9]中的方法可以获得关于扰动波数的下列色散关系:

$$k^2 = \frac{f_1 + f_2}{2} \pm \left[\left(\frac{f_1 + f_2}{2}\right)^2 + (C_{\mathrm{XPM}} - f_1 f_2)\right]^{1/2} \tag{11}$$

式中,

$$f_j = \frac{1}{2}\beta_{2j}\Omega_j^2 \times \left\{2\gamma_{1j}P_j' + 4\gamma_{2j}P_j'[P_j' + 3P_{3-j}'] + \frac{1}{2}\beta_{2j}\Omega_j^2\right\} \tag{12}$$

$$C_{\mathrm{XPM}} = 4\beta_{21}\beta_{22}\Omega_1^2\Omega_2^2P_1'P_2' \times \{\gamma_{11}\gamma_{12} + 3(P_1' + P_2')(\gamma_{11}\gamma_{22} + \gamma_{12}\gamma_{21}) + 9\gamma_{21}\gamma_{22}(P_1' + P_2')\} \tag{13}$$

$$P_j' = P_j\exp(-\alpha_j z) \tag{14}$$

由(11)式可知,对满足条件 $f_1 f_2 < C_{XPM}$ 的那些扰动频率,k成为复数,调制不稳定产生。扰动的功率增益系数为:

$$g(\Omega_1,\Omega_2)=2\mathrm{Im}(k)=\sqrt{2}\{[(f_1+f_2)^2+4(C_{XPM}-f_1 f_2)]^{1/2}-(f_1+f_2)\}^{1/2} \qquad (15)$$

由(11)式~(15)式可见,在三五阶非线性同时存在时,交叉相位调制的色散关系、根的形式以及调制不稳定的功率增益系数公式均与三阶非线性的情形类似[1,6~9],但式中参量 f_1, f_2 和 C_{XPM} 的定义则不同。

由(11)式~(15)式还可看出,交叉相位调制不稳定条件及增益谱与群色散系数、色散纵向变化参量、三阶和五阶非线性系数的正负和大小、扰动频率、损耗系数、两光波的入纤光功率以及传输距离等许多因素有关。前人的研究表明,对单光束而言,调制不稳定一般只能发生在光纤的负色散区,但对由两光波引起的交叉相位调制不稳定,则既可发生在光纤的负色散区,也可发生在正色散区。其中,当两光波同在光纤正色散区时,不稳定的频率范围最小,此时的调制不稳定完全由交叉相位调制引起[1],下面即针对此种情况进行讨论。

图1中给出了两光波同在色散缓变光纤正色散区时不同五阶非线性系数下的调制不稳定增益谱图。计算参数的选取参考了文献[11],在图1a、图1b和图1c中分别取 $|\Omega_1|/2\pi=0.3$THz, 1THz和2THz,其余各公共参数为: $\beta_{21}(0)=\beta_{22}(0)=20\mathrm{ps}^2\cdot\mathrm{km}^{-1}$, $\gamma_{11}=\gamma_{12}=1\mathrm{W}^{-1}\cdot\mathrm{km}^{-1}$, $P_1=P_2=400\mathrm{W}$, $z=5\mathrm{km}$, $\alpha_1=\alpha_2=0.3\mathrm{dB}\cdot\mathrm{km}^{-1}$, $\mu_1=\mu_2=0.3\mathrm{dB}\cdot\mathrm{km}^{-1}$。因 $g(\Omega_1,-\Omega_2)=g(\Omega_1,\Omega_2)$,故图中只画出了 $\Omega_2\geqslant 0$ 的那一半。由图1可见,在其它参数相同时,正五阶非线性使增益谱谱宽变宽,谱峰峰值变大且位置远离主波频率,即正五阶非线性可加强调制不稳定;而负五阶非线性则体现出折射率的饱和非线性,起抑制调制不稳定的作用。五阶非线性系数的绝对值越大,对调制不稳定的加强或抑制作用越明显。还可看出,扰动频率 $|\Omega_1|$ 不同,五阶非线性对交叉相位调制不稳定性的加强和抑制程度也不同。

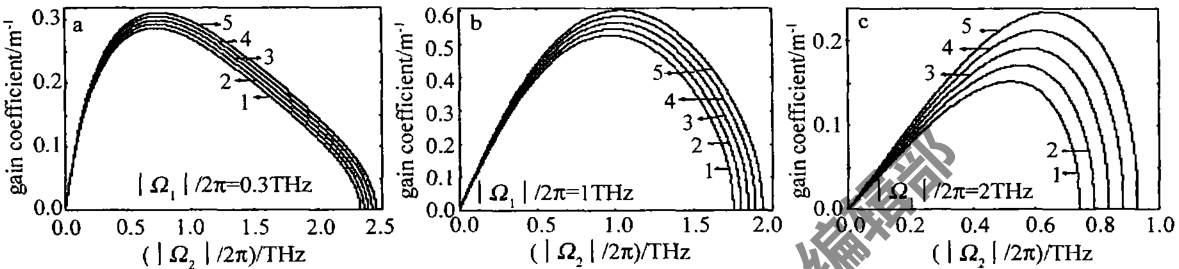

Fig 1　Gain spectra of modulation instability induced by cross-phase modulation in the normal dispersion region of decreasing dispersion optical fibers for different quintic nonlinear coefficients, 1—$\gamma_{21}=\gamma_{22}=-6\times10^{-5}\mathrm{W}^{-2}\cdot\mathrm{km}^{-1}$, 2—$\gamma_{21}=\gamma_{22}=-3\times10^{-5}\mathrm{W}^{-2}\cdot\mathrm{km}^{-1}$, 3—$\gamma_{21}=\gamma_{22}=0\mathrm{W}^{-2}\cdot\mathrm{km}^{-1}$, 4—$\gamma_{21}=\gamma_{22}=3\times10^{-5}\mathrm{W}^{-2}\cdot\mathrm{km}^{-1}$, 5—$\gamma_{21}=\gamma_{22}=6\times10^{-5}\mathrm{W}^{-2}\cdot\mathrm{km}^{-1}$

图2中给出了两光波同在色散缓变光纤正色散区时不同色散纵向变化参量下的调制不稳定增益谱图。在图2a、图2b和图2c中分别取 $|\Omega_1|/2\pi=0.3$THz, 1THz和2THz,各图中都取 $\gamma_{21}=\gamma_{22}=-6\times10^{-5}\mathrm{W}^{-5}\cdot\mathrm{km}^{-1}$,其余公共参数同图1。由图2可见,随着色散纵向变化参量的增加,增益谱的谱宽变宽,说明在五阶非线性下,色散系数的纵向渐减依然有利于产生调制不稳定。但是,随 $|\Omega_1|$ 的不同,色散纵向变化参量的变化对增益谱的大小和位置的影响也不同,在 $|\Omega_1|$ 较小时,见图2a,随着色散纵向变化参量的增加,谱宽增大,但谱峰峰值减小,谱峰位置变化不明显;在 $|\Omega_1|$ 稍大的图2b情况下,随着色散纵向变化参量的增加,谱宽也增大,谱峰位置远离主波频率,而谱峰峰值则先增大,后减小;当 $|\Omega_1|$ 较大时,见图2c,随着色散纵向变化参量的增加,增益谱宽和谱峰峰值都增大,谱峰位置远离主波频率。

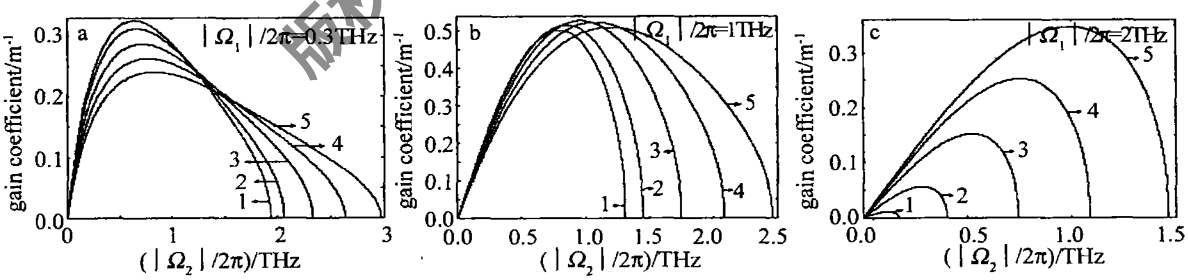

Fig 2　Gain spectra of modulation instability induced by cross-phase modulation in the normal dispersion region of decreasing dispersion optical fibers for different dispersion longitudinal varying parameters, 1—$\mu_1=\mu_2=0\mathrm{dB}\cdot\mathrm{km}^{-1}$, 2—$\mu_1=\mu_2=0.1\mathrm{dB}\cdot\mathrm{km}^{-1}$, 3—$\mu_1=\mu_2=0.3\mathrm{dB}\cdot\mathrm{km}^{-1}$, 4—$\mu_1=\mu_2=0.5\mathrm{dB}\cdot\mathrm{km}^{-1}$, 5—$\mu_1=\mu_2=0.7\mathrm{dB}\cdot\mathrm{km}^{-1}$

3 结　论

在三五阶非线性共存时, 研究了有损耗单模光纤中基于两光波交叉相位调制的不稳定条件和增益谱。在色散缓变光纤正色散区, 详细分析了五阶非线性系数、色散纵向变化参量以及两扰动的频率大小关系对交叉相位调制不稳定增益谱的影响。结果表明, 在五阶非线性下, 色散的纵向渐减仍然有利于展宽调制不稳定增益谱, 说明色散缓变光纤依然是产生调制不稳定的良好介质; 而正五阶非线性可使增益谱的谱宽和谱峰值增大, 并使谱峰位置远离主波频率, 负五阶非线性的作用则相反, 即正负五阶非线性分别对调制不稳定起加强和抑制作用; 两扰动频率大小关系不同, 色散纵向参量的变化对增益谱的谱峰大小和位置的影响也不同, 五阶非线性对交叉相位调制不稳定性的加强或抑制程度也不同。

参　考　文　献

[1] AGRAWAL G P. Nonlinear fiber optics [M]. 2nd ed, New York: Academic Press, 1995. 133~141.

[2] SYLVESTRE T, COEN S, EMPLIT P *et al*. Self-induced modulation instability laser revisited normal dispersion and dark-pulse train generation [J]. Opt Lett, 2002, 27(7): 482~484.

[3] GROSZ D F, MAZZALI C, CELASCHI S *et al*. Modulation instability induced resonant four-wave mixing in WDM systems [J]. IEEE Photonics Technology Letters, 1999, 11(3): 379~381.

[4] OKUNO T, ONISHI M, NISHIMURA M. Generation of ultra-broad-band super-continuum by dispersion-flattened and decreasing fiber [J]. IEEE Photonics Technology Letters, 1998, 10(1): 72~74.

[5] XU W C, ZHANG S M, CHEN W C *et al*. Modulation instability of femtosecond pulses in dispersion-decreasing fibers [J]. Opt Commun, 2001, 199: 355~360.

[6] XU W C, LUO A P, GUO Q *et al*. Modulation instability in decreasing dispersion fibers [J]. Acta Optica Sinica, 2000, 20(10): 1435~1439 (in Chinese).

[7] AGRAWAL G P, BALDECK P L, ALFANO R R. Modulation instability induced by cross-phase modulation in optical fibers [J]. Phys Rev, 1989, A39(7): 3406~3413.

[8] ZHONG X Q, LI D Y, CHEN J G. Further analysis of modulation instability induced by cross-phase modulation [J]. Laser Technology, 2004, 28(4): 427~430(in Chinese).

[9] YANG A L, WANG J, MIAO H L *et al*. Modulation instability gain spectrum of cross-phase modulation in decreasing dispersion fiber [J]. Laser Technology, 2003, 27(1): 44~46(in Chinese).

[10] PUSHKAROV D, TANEV S. Bright and dark solitary wave propagation and bistability in the anomalous dispersion region of optical waveguides with third- and fifth-order nonlinearities [J]. Opt Commun, 1996, 124: 354~364.

[11] PALACIOS S L, FERNÁNDEZ-DíAZ J M. Black optical solitons for media with parabolic nonlinearity law in the presence of fourth order dispersion [J]. Opt Commun, 2000, 178: 457~460.

[12] DIMITREVSKI K, REIMHULT E, SVENSSON E *et al*. Analysis of stable self-trapping of laser beams in cubic-quintic nonlinear media [J]. Phys Lett, 1998, A248: 369~376.

[13] HONG W P. Modulation instability of optical waves in the high dispersive cubic-quintic nonlinear Schrödinger equation [J]. Opt Commun, 2002, 213: 173~182.

[14] REN Z J, WANG J, YANG A L *et al*. Effect of quintic nonlinearity in the anomalous-dispersion regime of fiber [J]. Chinese Journal of Lasers, 2004, 31(5): 595~598(in Chinese).

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[15] FEI L G, ZHANG Sh L, WAN X J. Influence of optical feedback from birefringence external cavity on intensity tuning and polarization of laser [J]. Chinese Physics Letters, 2004, 21(10): 1944~1947.

[16] LACOT E, DAY R, STOECKEL F. Laser feedback tomography [J]. Opt Lett, 1999, 24(11): 744~746.

[17] SIEGMAN A E. Lasers [M]. Mill Valley, California: University Science, 1986. 1~1283.

[18] OTSUKA K, ABE K, KO J Y. Real-time nanometer vibration measurement with a self-mixing microchip solid-state laser [J]. Opt Lett, 2002, 27(15): 1339~1341.

[19] KAWAI R, ASAKAWA Y, OTSUKA K. Ultrahigh-sensitivity self-mixing laser Doppler velocimetry with laser diode-pumped microchip $LNdP_4O_{12}$ lasers [J]. IEEE Photon Technol Lett, 1999, 11(6): 706~708.

[20] OTSUKA K, KAWAI R, ASAKAWA Y *et al*. Highly sensitive self-mixing measurement of Brillouin scattering with a laser-diode-pumped microchip $LiNdP_4O_{12}$ laser [J]. Opt Lett, 1999, 24(24): 1862~1864.

[21] OKAMOTO S, TAKEDA H, KANNARI F. Ultrahighly sensitive laser-Doppler velocity meter with a diode-pumped Nd:YO_4 microchip laser [J]. Rev Scient Instrum, 1995, 66(5): 3116~3120.

[22] NERIN P, BESESTY P, LABEYE P *et al*. Absolute distance and velocity measurements by the FMCW technique and self-mixing interference effect inside a single-mode Nd:YAG-$LiTaO_3$ microchip laser [J]. J Optics (Paris), 1998, 29(3): 162~167.

[23] ABE K, OTSUKA K, KO J Y. Self-mixing laser Doppler vibrometry with high optical sensitivity: application to real-time sound reproduction [J]. New Journal of Physics, 2003, 5: 8.1~8.9.

[24] KO J Y, OHTOMO T, ABE K *et al*. Nonlinear dynamics and application of laser-diode-pumped microchip solid-state lasers [J]. International Journal of Modern Physics, 2001, B15(26): 3369~3395.

[25] NERIN P, PUGET P, BESESTY P *et al*. Self-mixing using a dual-polarization Nd:YAG microchip laser [J]. Electron Lett, 1997, 33(6): 491~492.

[26] WAN X J, ZHANG Sh L, FEI L G *et al*. Self-mixing interference in dual-polarization microchip Nd:YAG lasers [J]. Chinese Physics Letters, 2004, 21(11): 2175~2178.