Research Article

Optical Transition Probabilities of Er^{3+} Ions in $\text{ErBa}_3\text{B}_9\text{O}_{18}$ Crystal

Ming He,¹ Tiezheng Liu,² Junling Xiu,¹ Yuanguang Tang,¹ and Zhihua Zhang²

¹Department of Physics, College of Science, Dalian Jiaotong University, Dalian 116028, China

²Liaoning Key Materials Laboratory for Railway, College of Materials Science and Engineering, Dalian Jiaotong University, Dalian 116028, China

Correspondence should be addressed to Ming He; heming@djtu.edu.cn

Received 13 October 2014; Revised 24 December 2014; Accepted 24 December 2014

Academic Editor: Veer P. S. Awana

Copyright © 2015 Ming He et al. This is an open access article distributed under the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

The optical absorption and emission intensity of luminescent and birefringent crystal $\text{ErBa}_3\text{B}_9\text{O}_{18}$ were examined from optical absorption data based on Judd-Ofelt theory. The three intensity parameters Ω_t ($t = 2, 4, 6$) are 3.10×10^{-20} , 0.87×10^{-20} , and $1.80 \times 10^{-20} \text{ cm}^2$, respectively. From the obtained intensity parameters, the radiative probabilities A_r , radiative lifetime τ_f , fluorescence branching ratios β_c , and integrated emission cross sections Σ have been calculated. In comparison with other Er-doped luminescent crystals, $\text{ErBa}_3\text{B}_9\text{O}_{18}$ may find application in thin disk laser.

1. Introduction

Er^{3+} activator has attracted much attention for its two laser emissions at $2.94 \mu\text{m}$ ($^4\text{I}_{11/2} \rightarrow ^4\text{I}_{13/2}$) and $1.54 \mu\text{m}$ ($^4\text{I}_{13/2} \rightarrow ^4\text{I}_{15/2}$). The emissions have potential applications in optocommunication, sensors, or lidar system [1–3]. To now, the Er^{3+} ion has exhibited laser operations in various Er^{3+} -doped crystals or glasses [4–9]. For a laser crystal, the host material should be stable and efficient. Sometimes, the emission efficiency can be limited by the relatively low concentration of luminescent centers, because the quenching effect will occur if the Er^{3+} ions concentration is too high. Host material determines the luminescent efficiency of the laser crystal or phosphor in many cases. Thus, it is necessary to search for new materials with higher doping tolerance to enhance the performance of the laser.

Borates are well known for their applications in optical communications, nonlinear optics, luminescence material and lasers, and so forth [10–16]. A series of isostructural compounds $\text{RBa}_3\text{B}_9\text{O}_{18}$ ($\text{R} = \text{Y}, \text{Pr}, \text{Nd}, \text{Sm}, \text{Eu}, \text{Gd}, \text{Tb}, \text{Dy}, \text{Ho}, \text{Er}, \text{Tm}, \text{and Yb}$) [17, 18] were found to exhibit good luminescence properties under UV or X-ray excitations. These rare earth alkaline-earth isostructural compounds were first identified and structurally characterized by Li et al. [19].

They crystallize in centric space group $\text{P}6_3/\text{m}$ with lattice parameters of about $a = 7.17 \text{ \AA}$ and $c = 16.97 \text{ \AA}$. Three O atoms are bonded to one B atom and three BO_3 groups form a planar hexagonal $[\text{B}_3\text{O}_6]^{3-}$ ring [20]. The parallel arranged $[\text{B}_3\text{O}_6]^{3-}$ groups can separate the R^{3+} ions, which makes the energy migration between two rare earth ions difficult. Taking $\text{YBa}_3\text{B}_9\text{O}_{18}$ and $\text{ErBa}_3\text{B}_9\text{O}_{18}$ (EBBO) as examples, the shortest distance of two Y^{3+} or Er^{3+} ions is $7.16\text{--}7.17 \text{ \AA}$, which is long enough to limit the energy transfer between luminescent centers [20–22]. So, the quenching effect in EBBO is proved to be small and Er^{3+} may be an efficient luminescent center. The transition properties of the optical crystals can determine their luminescent performance. So, we performed the research on spectroscopic properties of EBBO.

2. Experimental

The crystals were grown by a pulling method [21]. An absorption spectrum was measured for EBBO using a crystal plate with faces (001) and about 0.4 mm thickness [23]. The absorption spectrum was measured from ultraviolet to infrared wavelength by the use of Lambda-900 UV-VIS-NIR spectrophotometer at room temperature.

FIGURE 1: The absorption spectra of EBBO crystal. This figure is from [23] with permission.

3. Results and Discussions

The spectrum presented in Figure 1 is measured in the wavelength ranges from 200 to 1700 nm. The strong absorption peaks related to Er^{3+} ions transitions can be assigned. The absorption bands located at 255, 376, 407, 485, 519, 650, 971, and 1539 nm corresponding to the transitions from $^4\text{I}_{15/2}$ to $^4\text{D}_{7/2}$, $^4\text{G}_{11/2}$, $^2\text{H}_{11/2}$, $^4\text{F}_{7/2}$, $^4\text{H}_{11/2}$, $^4\text{F}_{9/2}$, $^4\text{I}_{11/2}$, and $^4\text{I}_{13/2}$, respectively. These strong absorption peaks show mainly the eigenmultiplets typically observed in free Er^{3+} ions at similar spectral position due to the weak crystal field for rare earth ions. The absorption at 1539 nm is very strong, which indicated that the transition probability of $^4\text{I}_{15/2} \rightarrow ^4\text{I}_{13/2}$ is big, and the integrated emission cross section is expected to be great.

The Judd-Ofelt theory was applied to evaluate the optical transition probabilities of Er^{3+} ions in EBBO. Based on Judd-Ofelt theory of the parity-forbidden electric-dipole transitions of rare earth ions [24, 25], the electric and magnetic dipole line strengths of a transition from initial J_i level to the terminal J_t level are described by

$$S_{\text{ed}}(J_i, J_t) = \sum_{t=2,4,6} \Omega_t \left| \langle \Phi_{J_i} \| U^{(t)} \| \Phi_{J_t} \rangle \right|^2, \quad (1)$$

$$S_{\text{md}}(J_i, J_t) = \left(\frac{h}{4\pi mc} \right)^2 \sum_{t=2,4,6} \Omega_t \left| \langle \Phi_{J_i} \| L + 2S \| \Phi_{J_t} \rangle \right|^2,$$

where h is Planck's constant, c is the speed of light, m is the mass of electron, and $\langle \Phi_{J_i} \| U^{(t)} \| \Phi_{J_t} \rangle$ is the reduced matrix elements depending on the Er^{3+} ions. In this work, the values of the squares of the reduced matrix elements are cited from Carnall's calculations [26]. Ω_t ($t = 2, 4, 6$) are the three intensity parameters related to crystal field. Magnetic dipole line strengths are very small compared to electric ones and can be neglected in the calculation of the parameters except for $^4\text{I}_{15/2} \rightarrow ^4\text{I}_{13/2}$. The value of S_{md} is cited from [27] to be

$0.683 \times 10^{-20} \text{ cm}^2$ because S_{md} does not vary with the host crystal.

Then the measured line strengths $S_{\text{ed}}^{\text{meas}}(J_i, J_t)$ from the absorption spectrum can be given by

$$S_{\text{ed}}^{\text{meas}}(J_i, J_t) = \frac{9n}{(n^2 + 2)^2} \left[\frac{3ch}{8\pi^3 e^2} \frac{2J + 1}{N_c} \frac{2.303}{\lambda d} \times \int_{J_i \rightarrow J_t} \text{OD}(\lambda) d\lambda - nS_{\text{md}} \right], \quad (2)$$

where λ is the mean wavelength of the absorption band, $\text{OD}(\lambda)$ presents the measured optical density, and d is the thickness of the crystal. The concentration of Er^{3+} ions N_c in $\text{ErBa}_3\text{B}_9\text{O}_{18}$ is calculated based on the crystal structure parameter. The crystal structure of $\text{ErBa}_3\text{B}_9\text{O}_{18}$ adopts a centric space group $\text{P6}_3/\text{m}$ and the lattice parameters are $a = 7.1817 \text{ \AA}$ and $c = 16.996 \text{ \AA}$ [21]. There are two Er^{3+} in one unit cell, so N_c is calculated to be $2.63 \times 10^{27}/\text{m}^3$. n is the refractive index, which can be obtained by Sellmeier's equation [21], and e is the electron charge. Table 1 presents the line strengths S_{ed} of nine absorption peaks of Er^{3+} in crystal. Three intensity parameters Ω_t ($t = 2, 4, 6$) were fitted by least-square method to be 3.10×10^{-20} , 0.87×10^{-20} , and $1.80 \times 10^{-20} \text{ cm}^2$.

From Judd-Ofelt theory, the electric-dipole and magnetic-dipole contributions, A_{ed} and A_{md} , of the total spontaneous emission probability are given by

$$A_{JJ'} = A_{\text{ed}} + A_{\text{md}}$$

$$= \frac{64\pi^4 e^2}{3h(2J + 1)\lambda^3} \left[\frac{n(n^2 + 2)^2}{9} S_{\text{ed}} + n^3 S_{\text{md}} \right] \quad (3)$$

$$= 165.3 + 43.8 = 209.1 \text{ (s}^{-1}\text{)}.$$

The luminescence parameters can be calculated from the following equations:

$$A_{JJ'} = \frac{64\pi^4 e^2}{3h(2J + 1)\lambda^3} \left[\frac{n(n^2 + 2)^2}{9} S_{\text{ed}} + n^3 S_{\text{md}} \right]$$

$$\frac{1}{\tau_r} = \sum_{J'} A_{JJ'} \quad (4)$$

$$\beta_c = \frac{A_{JJ'}}{\sum_{J'} A_{JJ'}}$$

$$\sum_{JJ'} = \frac{A_{JJ'} \lambda^2}{8\pi c n^2},$$

where β_c is the fluorescence branch ratio, τ_r is the radiative lifetime of a given upper level, $A_{JJ'}$ is the transition probability of spontaneous emission, and $\sum_{JJ'}$ is the integrated emission cross section. The calculated results are listed in Table 2.

The results show that radiative probabilities (209 s^{-1}) of $^4\text{I}_{15/2} \rightarrow ^4\text{I}_{13/2}$ are comparable to those of $\text{Er}:\text{YAG}$ (211 s^{-1})

TABLE 1: Calculated strength parameters for Er^{3+} in EBBO.

Peak	Configuration	Wavelength (nm)	$\int \text{OD}(\lambda)d\lambda$ (nm)	S_{meas} (10^{-20} cm^2)	S_{cal} (10^{-20} cm^2)	$\Delta s.^2$
1	$^4\text{I}_{13/2}$	1539	25.73	3.27	2.76	0.26
2	$^4\text{I}_{11/2}$	971	0.83	0.20	0.80	0.36
3	$^4\text{F}_{9/2}$	650	2.09	0.75	1.32	0.32
4	$^4\text{H}_{11/2}$	519	5.35	2.37	2.72	0.12
5	$^4\text{F}_{7/2}$	485	1.97	0.94	1.27	0.11
6	$^2\text{H}_{9/2}$	407	0.53	0.29	0.43	0.02
7	$^4\text{G}_{11/2}$	376	6.29	3.77	3.50	0.08
8	$^4\text{D}_{7/2}$	255	1.35	1.18	0.85	0.11

$\text{Rms-}\Delta s. = 0.40 \times 10^{-20} \text{ cm}^2$, $\Omega_{2,4,6} = (3.10, 0.87, 1.80) \times 10^{-20} \text{ cm}^2$

TABLE 2: The spectral parameters for Er^{3+} ions in EBBO crystal.

Transitions	Wavelength (nm)	A_{ed} (s^{-1})	A_{md} (s^{-1})	τ_r (μs)	β_c	$\sum_{J'J''} (10^{-18} \text{ cm})$
$^4\text{I}_{13/2} \rightarrow ^4\text{I}_{15/2}$	1539	165.28	43.76	4783	1	2.243
$^4\text{I}_{11/2} \rightarrow ^4\text{I}_{15/2}$	971	233.32		3733	0.87	1.00
$^4\text{I}_{11/2} \rightarrow ^4\text{I}_{13/2}$	2778	25.85	8.68		0.13	1.212
$^4\text{F}_{9/2} \rightarrow ^4\text{I}_{15/2}$	650	1583.41		568	0.90	3.03
$^4\text{F}_{9/2} \rightarrow ^4\text{I}_{13/2}$	1156	68.49			0.04	0.42
$^4\text{F}_{9/2} \rightarrow ^4\text{I}_{11/2}$	1980	104.75			0.06	1.86
$^4\text{F}_{9/2} \rightarrow ^4\text{I}_{9/2}$	3448	2.59			0.00	0.14
$^4\text{S}_{3/2} \rightarrow ^4\text{I}_{13/2}$	844	852.40		983	0.83	2.75
$^4\text{S}_{3/2} \rightarrow ^4\text{I}_{11/2}$	1212	66.72			0.07	0.44
$^4\text{S}_{3/2} \rightarrow ^4\text{I}_{9/2}$	1639	97.38			0.10	1.19
$^2\text{H}_{9/2} \rightarrow ^4\text{I}_{15/2}$	407	1616.62		238	0.38	1.21
$^2\text{H}_{9/2} \rightarrow ^4\text{I}_{13/2}$	555	2044.55			0.49	2.86
$^2\text{H}_{9/2} \rightarrow ^4\text{I}_{11/2}$	703	477.28			0.11	1.07
$^2\text{H}_{9/2} \rightarrow ^4\text{I}_{9/2}$	841	18.100			0.01	0.06
$^2\text{H}_{9/2} \rightarrow ^4\text{F}_{9/2}$	1089	41.36			0.01	0.22
$^4\text{G}_{11/2} \rightarrow ^4\text{I}_{15/2}$	376	19505.40				
$^4\text{D}_{7/2} \rightarrow ^4\text{I}_{15/2}$	255	22544.50				
$^4\text{I}_{9/2} \rightarrow ^4\text{I}_{13/2}$	1739	72.16				
$^4\text{H}_{11/2} \rightarrow ^4\text{I}_{15/2}$	519	5420.35				
$^4\text{F}_{7/2} \rightarrow ^4\text{I}_{15/2}$	485	4658.79				

[28], $\text{Er}_x\text{Y}_{1-x}\text{Al}_3(\text{BO}_3)_4$ (233 s^{-1}) [29], and $\text{Er}:\text{La}_2\text{CaB}_{10}\text{O}_{19}$ (262 s^{-1}) [30]. The integrated emission cross section of 1539 nm is $2.24 \times 10^{-18} \text{ cm}$, which indicates that large amplification gains near $1.54 \mu\text{m}$ are expected to be obtained. So the crystal has the potential to be a laser material with good chemical and physical properties. What is more, due to the high concentrations of Er^{3+} activators, EBBO may find applications in thin disk laser.

4. Conclusion

The spectroscopic properties of $\text{ErBa}_3\text{B}_9\text{O}_{18}$ crystal have been investigated at room temperature. The Judd-Ofelt theory has been applied to evaluate the optical transition probabilities of Er^{3+} ions in $\text{ErBa}_3\text{B}_9\text{O}_{18}$. Based on the Judd-Ofelt theory, the intensity parameters obtained by the least-square fitting method Ω_t ($t = 2, 4, 6$) are 3.10×10^{-20} , 0.87×10^{-20} , and $1.80 \times$

10^{-20} cm^2 , respectively. The radiative probabilities, lifetime, and fluorescence branching ratios have been calculated. Compared with other Er-doped laser crystals, $\text{ErBa}_3\text{B}_9\text{O}_{18}$ crystal has large integrated emission cross sections and radiative probabilities. With good chemical and physical properties, $\text{ErBa}_3\text{B}_9\text{O}_{18}$ may find application in thin disk laser.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

Acknowledgment

The authors gratefully acknowledge the support from the National Natural Science Foundation of China (Grant nos. 51372026 and 51372027).

References

- [1] Y. Ding, S. Jiang, B.-C. Hwang et al., "Spectral properties of erbium-doped lead halotellurite glasses for 1.5 μm broadband amplification," *Optical Materials*, vol. 15, no. 2, pp. 123–130, 2000.
- [2] J. Breguet, A. F. Umyskov, S. G. Semenov, W. Luthy, H. P. Weber, and I. A. Shcherbakov, "Comparison of threshold energy of selectively excited $\text{YAlO}_3\text{:Er}$ and YAG:Er lasers," *IEEE Journal of Quantum Electronics*, vol. 28, no. 11, pp. 2563–2566, 1992.
- [3] M. Yamada, "Broadband and gain-flattened amplifier composed of a 1.55 [micro sign]m-band and a 1.58 [micro sign]m-band Er^{3+} -doped fibre amplifier in a parallel configuration," *Electronics Letters*, vol. 33, no. 8, p. 710, 1997.
- [4] V. P. Gapontsev, S. M. Matitsin, A. A. Isineev, and V. B. Kravchenko, "Erbium glass lasers and their applications," *Optics & Laser Technology*, vol. 14, no. 4, pp. 189–196, 1982.
- [5] J. D. Bradley, J. Dinnerman, and P. F. Moulton, "3- μm cw laser operations in erbium-doped YSGG, GGG, and YAG," *Optics Letters*, vol. 19, no. 15, pp. 1143–1145, 1994.
- [6] G. J. Kintz, R. Allen, and L. Esterowitz, "CW and pulsed 2.8 μm laser emission from diode-pumped $\text{Er}^{3+}\text{:LiYF}_4$ at room temperature," *Applied Physics Letters*, vol. 50, p. 1553, 1987.
- [7] H. Stange, K. Peterman, G. Huber, and E. W. Duczynski, "Continuous wave 1.6 μm laser action in Er doped garnets at room temperature," *Applied Physics B*, vol. 49, no. 3, pp. 269–273, 1989.
- [8] F. Auzel, S. Hubert, and D. Meichenin, "Multifrequency room-temperature continuous diode and Ar^* laser-pumped Er^{3+} laser emission between 2.66 and 2.85 μm ," *Applied Physics Letters*, vol. 54, no. 8, p. 681, 1989.
- [9] N. Van Minh, N. Manh Hung, D. Thi Xuan Thao, M. Roef-faers, and J. Hofkens, "Structural and optical properties of $\text{ZnWO}_4\text{:Er}^{3+}$ crystals," *Journal of Spectroscopy*, vol. 2013, Article ID 424185, 5 pages, 2013.
- [10] L. Wu, X. L. Chen, Q. Y. Tu et al., "Phase relations in the system $\text{Li}_2\text{O-MgO-B}_2\text{O}_3$," *Journal of Alloys and Compounds*, vol. 333, no. 1–2, pp. 154–158, 2002.
- [11] R. C. Stoneman and L. Esterowitz, "Efficient resonantly pumped 28- μm $\text{Er}^{3+}\text{:GSGG}$ laser," *Optics Letters*, vol. 17, no. 11, p. 816, 1992.
- [12] C. Chen, B. Wu, A. Jiang, and G. You, "A new-type ultraviolet SHG crystal $\beta\text{-BaB}_2\text{O}_4$," *Scientia Sinica B*, vol. 28, no. 3, pp. 235–243, 1985.
- [13] M. He, X. L. Chen, H. Okudera, and A. Simon, " $(\text{K}_{1-x}\text{Na}_x)_2\text{Al}_2\text{B}_2\text{O}_7$ with $0 \leq x < 0.6$: a promising nonlinear optical crystal," *Chemistry of Materials*, vol. 17, no. 8, pp. 2193–2196, 2005.
- [14] C. Chen, Y. Wu, A. Jiang et al., "New nonlinear-optical crystal: LiB_3O_5 ," *Journal of the Optical Society of America B*, vol. 6, no. 4, pp. 616–621, 1989.
- [15] L. Wu, X. L. Chen, H. Li, M. He, Y. P. Xu, and X. Z. Li, "Structure determination and relative properties of novel cubic borates $\text{MM}'_4(\text{BO}_3)_3$ ($\text{M} = \text{Li}$, $\text{M}' = \text{Sr}$; $\text{M} = \text{Na}$, $\text{M}' = \text{Sr}$, Ba)," *Inorganic Chemistry*, vol. 44, pp. 6409–6414, 2005.
- [16] C. Chen, Y. Wu, and R. Li, "The relationship between the structural type of anionic group and SHG effect in boron-oxygen compounds," *Chinese Physics Letters*, vol. 2, no. 9, p. 389, 1985.
- [17] C. Duan, J. Yuan, and J. Zhao, "Luminescence properties of efficient X-ray phosphors of $\text{YBa}_3\text{B}_9\text{O}_{18}$, $\text{LuBa}_3(\text{BO}_3)_3$, $\alpha\text{-YBa}_3(\text{BO}_3)_3$ and LuBO_3 ," *Journal of Solid State Chemistry*, vol. 178, no. 12, pp. 3698–3702, 2005.
- [18] C. Duan, J. Yuan, X. Yang et al., "Luminescent properties of $\text{REBa}_3\text{B}_9\text{O}_{18}$ ($\text{RE} = \text{Lu}$, Tb , Gd , Eu) under VUV excitation," *Journal of Physics D: Applied Physics*, vol. 38, no. 19, p. 3576, 2005.
- [19] X. Z. Li, C. Wang, X. L. Chen et al., "Syntheses, thermal stability, and structure determination of the novel isostructural $\text{RBA}_3\text{B}_9\text{O}_{18}$ ($\text{R} = \text{Y}$, Pr , Nd , Sm , Eu , Gd , Tb , Dy , Ho , Er , Tm , Yb)," *Inorganic Chemistry*, vol. 43, no. 26, pp. 8555–8560, 2004.
- [20] M. He, W. Y. Wang, Y. P. Sun, Y. P. Xu, and X. L. Chen, "Growth and optical properties of $\text{YBa}_3\text{B}_9\text{O}_{18}\text{:Ce}$ crystals," *Journal of Crystal Growth*, vol. 307, no. 2, pp. 427–431, 2007.
- [21] M. He, G. M. Cai, W. J. Wang, W. Y. Wang, J. Liu, and X. L. Chen, "Growth and luminescence properties of a novel crystal with large birefringence: $\text{ErBa}_3\text{B}_9\text{O}_{18}$," *Journal of Crystal Growth*, vol. 311, no. 4, pp. 1234–1237, 2009.
- [22] M. He, X. L. Chen, Y. P. Sun, J. Liu, J. T. Zhao, and C. J. Duan, " $\text{YBa}_3\text{B}_9\text{O}_{18}$: a promising scintillation crystal," *Crystal Growth & Design*, vol. 7, no. 2, pp. 199–201, 2007.
- [23] M. He, T. Z. Liu, M. H. Qiu et al., "Study on the optical properties of $\text{ErBa}_3\text{B}_9\text{O}_{18}$ crystals," *Physica B: Condensed Matter*, vol. 456, pp. 100–102, 2015.
- [24] B. R. Judd, "Optical absorption intensities of rare-earth ions," *Physical Review*, vol. 127, no. 3, pp. 750–761, 1962.
- [25] G. S. Ofelt, "Intensities of crystal spectra of rare-earth ions," *The Journal of Chemical Physics*, vol. 37, no. 3, p. 511, 1962.
- [26] W. T. Carnall, P. R. Fields, and K. Rajnak, "Electronic energy levels in the trivalent lanthanide aquo ions. I. Pr^{3+} , Nd^{3+} , Pm^{3+} , Sm^{3+} , Dy^{3+} , Ho^{3+} , Er^{3+} , and Tm^{3+} ," *The Journal of Chemical Physics*, vol. 49, p. 4424, 1968.
- [27] W. T. Carnall, P. R. Fields, and K. Rajnak, "Electronic energy levels in the trivalent lanthanide aquo ions. I. Pr^{3+} , Nd^{3+} , Pm^{3+} , Sm^{3+} , Dy^{3+} , Ho^{3+} , Er^{3+} , and Tm^{3+} ," *The Journal of Chemical Physics*, vol. 49, no. 10, pp. 4414–4442, 1968.
- [28] R. Reisfeld, *The Rare Earths in Modern Sciences and Technology*, Plenum Press, New York, NY, USA, 1979.
- [29] M. G. Liu, B. S. Lu, H. F. Pan, and Q. Song, " $\text{Er}_x\text{Y}_{1-x}\text{Al}_3(\text{BO}_3)_4$ crystal growth and its spectral properties," *Acta Optical Sinica*, vol. 8, pp. 1079–1084, 1988.
- [30] R. Guo, Y. Wu, P. Fu, and F. Jing, "Optical transition probabilities of Er^{3+} ions in $\text{La}_2\text{CaB}_{10}\text{O}_{19}$ crystal," *Chemical Physics Letters*, vol. 416, no. 1–3, pp. 133–136, 2005.