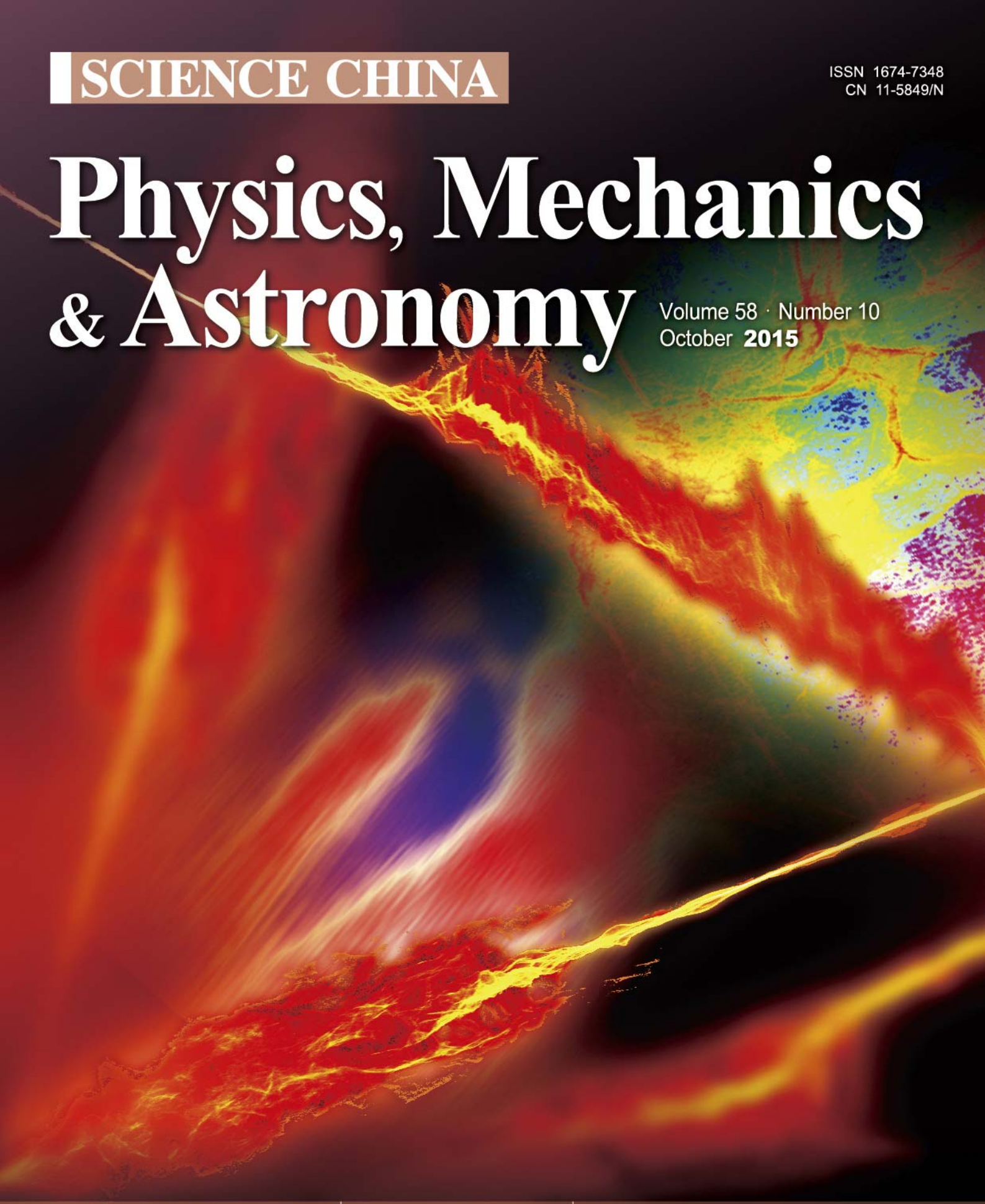
SCIENCE CHINA

ISSN 1674-7348
CN 11-5849/N

Physics, Mechanics & Astronomy

Volume 58 · Number 10
October **2015**



SCIENCE CHINA PRESS

Springer

Chinese Academy of Sciences
National Natural Science Foundation of China

Ownership by Science China Press; Copyright©2015 by Science China Press, Beijing, China and Springer-Verlag Heidelberg, Germany

Submission of a manuscript implies: that the work described has not been published before (except in the form of an abstract or as part of a published lecture, review, or thesis); that it is not under consideration for publication elsewhere; that its publication has been approved by all co-authors, if any, as well as–tacitly or explicitly–by the responsible authorities at the institution where the work was carried out. The author warrants that his/her contribution is original and that he/she has full power to make this grant. The author signs for and accepts responsibility for releasing this material on behalf of any and all co-authors. Transfer of copyright to Science China Press and Springer becomes effective if and when the article is accepted for publication. After submission of the Copyright Transfer Statement signed by the corresponding author, changes of authorship or in the order of the authors listed will not be accepted by Science China Press and Springer. The copyright covers the exclusive right (for U.S. government employees: to the extent transferable) to reproduce and distribute the article, including reprints, translations, photographic reproductions, microform, electronic form (offline, online) or other reproductions of similar nature.

An author may self-archive an author-created version of his/her article on his/her own website. He/she may also deposit this version on his/her institution's and funder's (funder designated) repository at the funder's request or as a result of a legal obligation, including his/her final version, provided it is not made publicly available until after 12 months of official publication. He/she may not use the publisher's PDF version which is posted on link.springer.com for the purpose of self-archiving or deposit. Furthermore, the author may only post his/her version provided acknowledgement is given to the original source of publication and a link is inserted to the published article on Springer's website. The link must be accompanied by the following text: "The original publication is available at link.springer.com".

All articles published in this journal are protected by copyright, which covers the exclusive rights to reproduce and distribute the article (e.g., as offprints), as well as all translation rights. No material published in this journal may be reproduced photographically or stored on microfilm, in electronic data bases, video disks, etc., without first obtaining written permission from the publishers. The use of general descriptive names, trade names, trademarks, etc., in this publication, even if not specifically identified, does not imply that these names are not protected by the relevant laws and regulations.

While the advice and information in this journal is believed to be true and accurate at the date of its going to press, neither the authors, the editors, nor the publishers can accept any legal responsibility for any errors or omissions that may be made. The publisher makes no warranty, express or implied, with respect to the material contained herein.

Special regulations for photocopies in the USA: Photocopies may be made for personal or in-house use beyond the limitations stipulated under Section 107 or 108 of U.S. Copyright Law, provided a fee is paid. All fees should be paid to the Copyright Clearance Center, Inc., 222 Rosewood Drive, Danvers, MA 01923, USA, Tel.: +1-978-7508400, Fax: +1-978-6468600, http://www.copyright.com, stating the ISSN of the journal, the volume, and the first and last page numbers of each article copied. The copyright owner's consent does not include copying for general distribution, promotion, new works, or resale. In these cases, specific written permission must first be obtained from the publishers.

Abstracted/indexed in:

SCI, EI, Aerospace & High Technology Database, Astrophysics Data System, Current Contents, Computer and Information Systems Abstracts, CSA Materials Research Database with METADEX, Google Scholar, Index to Scientific Reviews, INSPEC, Mathematical Reviews, Mechanical and Transportation Engineering Abstracts, Solid State and Superconductivity Abstracts, World Ceramics Abstracts, etc.

SCIENCE CHINA Physics, Mechanics & Astronomy Vol. 58 No. 10 October 2015 (Monthly)

Supervised by Chinese Academy of Sciences
Sponsored by Chinese Academy of Sciences and National Natural Science Foundation of China
Published jointly by Science China Press and Springer
Subscriptions
China Science China Press, 16 Donghuangchenggen North Street, Beijing 100717, China
Email: sales@scichina.org Fax: 86-10-64016350
North and South America Springer New York, Inc., Journal Fulfillment, P.O. Box 2485, Secaucus, NJ 07096 USA
Email: journals-ny@springer.com Fax: 1-201-348-4505
Outside North and South America Springer Distribution Center, Customer Service Journals, Haberstr. 7, 69126 Heidelberg, Germany
Email: subscriptions@springer.com Fax: 49-6221-345-4229
Printed by Beijing Artownprinting Co., Ltd., Chuangyeyuan Road, Taihu town, Tongzhou District, Beijing 101116, China
Edited by Editorial Board of SCIENCE CHINA Physics, Mechanics & Astronomy, 16 Donghuangchenggen North Street, Beijing 100717, China
Editors-in-Chief WANG DingSheng ZHANG Jie

CN 11-5849/N 邮发代号: 80-212
广告经营许可证: 京东工商广字第 0429 号 国内每期定价: 145 元

Go To Website

SCIENCE CHINA
Physics, Mechanics & Astronomy

Contents

Vol. 58 No.10 October 2015

Invited Review

Condensed Matter Physics

Research trends in electron-doped cuprate superconductors 107401
YUAN Jie, HE Ge, YANG Hua, SHI YuJun, ZHU BeiYi & JIN Kui

Articles

Quantum Physics

QKD-based quantum private query without a failure probability 100301
LIU Bin, GAO Fei, HUANG Wei & WEN QiaoYan

Nuclear Physics

A short revisit to Kuo-Brown effective interactions 102001
WANG XiaoBao & DONG GuoXiang

Optics

Experimental study of balanced optical homodyne and heterodyne detection by controlling sideband modulation 104201
LI Wei, YU XuDong, MENG ZengMing, JIN YuanBin & ZHANG Jing

Fluid Dynamics

Numerical simulation of powder transport behavior in laser cladding with coaxial powder feeding 104701
LIU Hao, HE XiuLi, YU Gang, WANG ZhongBin, LI ShaoXia, ZHENG CaiYun & NING WeiJian

A hybrid CFD/characteristics method for fast characterization of hypersonic blunt forebody/inlet flow 104702
GAO WenZhi, LI ZhuFei & YANG JiMing

Aerothermal characteristics of bleed slot in hypersonic flows 104703
YUE LianJie, LU HongBo, XU Xiao & CHANG XinYu

Evaluating the accuracy performance of Lucas-Kanade algorithm in the circumstance of PIV application 104704
PAN Chong, XUE Dong, XU Yang, WANG JinJun & WEI RunJie

Plasma Physics

Two-stage acceleration of interstellar ions driven by high-energy lepton plasma flows 105201
CUI YunQian, SHENG ZhengMing, LU QuanMing, LI YuTong & ZHANG Jie

Condensed Matter Physics

Two-dimensional silicon-carbon hybrids with a honeycomb lattice: New family for two-dimensional photovoltaic materials 106801
ZHANG Jin, REN Jun, FU HuiXia, DING ZiJing, LI Hui & MENG Sheng

Cover The origin of high-energy cosmic-rays over a wide range of energies is still among the most fundamental problems in astrophysics. The authors of this work have reconsidered a scenario supposed to be relevant to cosmic-ray generation via self-consistent large-scale numerical simulation, i.e., the transport of a high-energy lepton plasma flow (composed of electron and positron pairs) through a background plasma (composed of electrons and protons). They have discovered unique two-stage acceleration processes of background protons. Strong turbulent electric and magnetic fields are formed first in this system via the Weibel-type instability and both background electrons and protons are stochastically accelerated in the fields. In particular, accelerated protons have a perfect inverse-power energy spectrum, typical for Fermi II acceleration. Moreover, a collisionless shockwave structure emerges gradually later along the same direction as the injected lepton flow, which further accelerates some background protons longitudinally. The front cover image is an artistic picture of turbulent field structures and accelerated particles (see the article No. 105201 by CUI YunQian et al.)

Nanoscale superconductivity of γ-Ga islands grown by molecular beam epitaxy 107402
ZHANG HuiMin, PENG JunPing, GUAN JiaQi, LI Zhi, SONG CanLi, WANG LiLi, HE Ke, MA XuCun & XUE QiKun

CVD synthesis of nitrogen-doped graphene using urea..... 107801
ZHANG CanKun, LIN WeiYi, ZHAO ZhiJuan, ZHUANG PingPing, ZHAN LinJie, ZHOU YingHui & CAI WeiWei

Astrophysics

Electrically charged: An effective mechanism for soft EOS supporting massive neutron star..... 109501
JING ZhenZhen, WEN DeHua & ZHANG XiangDong

Letter

Solid Mechanics

Effect of Zn particles on ductility of the accumulative roll-bonding composites 104601
LIU ChongYu, MA MingZhen, LIU RiPing, YU Liang & LUO Kun

Editorial Board

Supported by NSFC

Honorary Editor General **ZHOU GuangZhao (Zhou Guang Zhao)**

Editor General **ZHU ZuoYan** *Institute of Hydrobiology, Chinese Academy of Sciences*

Editors-in-Chief **WANG DingSheng** *Institute of Physics, Chinese Academy of Sciences*

ZHANG Jie *Shanghai Jiao Tong University*

Executive Associate Editor-in-Chief **GONG QiHuang** *School of Physics, Peking University*

Associate Editors-in-Chief

FENG ShiPing *Department of Physics, Beijing Normal University*
FU Song *School of Aerospace, Tsinghua University*
HONG YouShi *Institute of Mechanics, Chinese Academy of Sciences*
HU GengKai *School of Aerospace Engineering, Beijing Institute of Technology*
JI XiangDong *Department of Physics and Astronomy, Shanghai Jiao Tong University*
JIN XiaoFeng *Department of Physics, Fudan University*
JING YiPeng *Department of Physics and Astronomy, Shanghai Jiao Tong University*
LI ShuShen *Institute of Semiconductors, Chinese Academy of Sciences*
LIAO XinHao *Shanghai Astronomical Observatory, Chinese Academy of Sciences*
LONG GuiLu *Department of Physics, Tsinghua University*
XU RenXin *Department of Astronomy, School of Physics, Peking University*
ZHANG ZhaoXi *Institute of Theoretical Physics, Chinese Academy of Sciences*

Associate Editors

Physics I

CHEN NanXian *Center of Condensed Physics, Tsinghua University*
DAI Ning *Shanghai Institute of Technical Physics, Chinese Academy of Sciences*
HONG MingHui *Department of Electrical and Computer Engineering, Faculty of Engineering, National University of Singapore*
JIANG HongBing *School of Physics, Peking University*
JIN KuiJuan *Institute of Physics, Chinese Academy of Sciences*
LIU Ming *Institute of Microelectronics, Chinese Academy of Science*
LU ZhengHong *Department of Materials Science and Engineering, University of Toronto*
SHI Jing *Department of Physics & Astronomy, University of California, Riverside*
WU JunQiao *Department of Materials Science and Engineering, University of California, Berkeley*
WANG WeiHua *Institute of Physics, Chinese Academy of Sciences*
WANG LiJun *Department of Physics, Tsinghua University*
WANG Wei *School of Physics, Nanjing University*
WEN HaiHu *School of Physics, Nanjing University*
XIE XinCheng *School of Physics, Peking University*
YANG JinLong *Department of Chemical Physics, University of Science and Technology of China*
YUAN JianMin *College of Science, National University of Defense Technology*
ZHANG HaiLan *Institute of Acoustics, Chinese Academy of Sciences*
ZHANG Jing *Institute of Opto-Electronics, Shanxi University*
ZHANG RenHe *Institute of Acoustics, Chinese Academy of Sciences*
ZHANG ShuYi *Institute of Acoustics, School of Physics, Nanjing University*

Physics II

CHEN XiaoSong *Institute of Theoretical Physics, Chinese Academy of Sciences*
FEI ShaoMing *School of Mathematical Sciences, Capital Normal University*
HE XianTu *Institute of Applied Physics and Computational Mathematics*
HU HongBo *Institute of High Energy Physics, Chinese Academy of Sciences*
HUANG ChaoGuang *Institute of High Energy Physics, Chinese Academy of Sciences*
LI Miao *Institute of Astronomy and Space Science, Sun Yat-sen University*
LIU WeiPing *China Institute of Atomic Energy*
LUO MinXing *Zhejiang Institute of Modern Physics, Physics Department, Zhejiang University*
REN ZhongZhou *Department of Physics, Nanjing University*
SHEN XiaoYan *Institute of High Energy Physics, Chinese Academy of Sciences*
SHENG ZhengMing *Department of Physics and Astronomy, Shanghai Jiao Tong University*
SU ShuFang *Department of Physics, University of Arizona*

SUN ChangPu	*Beijing Computational Science Research Center, China Academy of Engineering Physics*
TANG XiaoWei	*Department of Physics, Zhejiang University*
TIAN Lin	*School of Natural Sciences, University of California, Merced*
WANG XinNian	*Lawrence Berkeley National Laboratory*
XU Nu	*Lawrence Berkeley National Laboratory*
YAO WeiMing	*Lawrence Berkeley National Laboratory*
YE YanLin	*School of Physics, Peking University*
ZHAO Hong	*Department of Physics, Xiamen University*
ZHOU ShanGui	*Institute of Theoretical Physics, Chinese Academy of Sciences*
ZHUANG PengFei	*Department of Physics, Tsinghua University*
ZUO Wei	*Institute of Modern Physics, Chinese Academy of Sciences*

Mechanics

HU Hui	*Department of Aerospace Engineering, Iowa State University*
JIN DongPing	*State Key Laboratory of Mechanics and Control of Mechanical Structures, Nanjing University of Aeronautics and Astronautics*
KONTIS Konstantinos	*School of Engineering, University of Glasgow*
LI JiaChun	*Institute of Mechanics, Chinese Academy of Sciences*
LI JunFeng	*School of Aerospace, Tsinghua University*
LI ShaoFan	*Department of Civil and Environmental Engineering, University of California-Berkeley*
LIAO ShiJun	*School of Naval Architecture, Ocean and Civil Engineering, Shanghai Jiao Tong University*
LONG Mian	*Institute of Mechanics, Chinese Academy of Sciences*
LUO Hong	*Department of Mechanical and Aerospace Engineering, North Carolina State University*
QIU ZhiPing	*Institute of Solid Mechanics, Beihang University*
RU ChongQing	*Department of Mechanical Engineering, University of Alberta*
RUZZENE Kassimo	*School of Aerospace and Mechanical Engineering, Georgia Institute of Technology*
SHE ZhenSu	*College of Engineering, Peking University*
WU ChuiJie	*School of Aeronautics and Astronautics, Dalian University of Technology*
YANG JiMing	*Department of Modern Mechanics, University of Science and Technology of China*
ZHAO YaPu	*Institute of Mechanics, Chinese Academy of Sciences*
ZHENG XiaoJing	*Xidian University*
ZHONG Zheng	*School of Aerospace Engineering and Applied Mechanics, Tongji University*

Astronomy

CHEN PengFei	*School of Astronomy and Space Science, Nanjing University*
GAO Yu	*Purple Mountain Observatory, Chinese Academy of Sciences*
GE Jian	*Department of Astronomy, University of Florida*
HAN ZhanWen	*Yunnan Astronomical Observatory, Chinese Academy of Sciences*
JI PeiWen	*National Natural Science Foundation of China*
LI AiGen	*Department of Physics & Astronomy, University of Missouri*
LI LiXin	*Kavli Institute for Astronomy and Astrophysics, Peking University*
MAO ShuDe	*National Astronomical Observatories, Chinese Academy of Sciences*
QIAN YongZhong	*School of Physics and Astronomy, University of Minnesota*
XIAO Long	*Faculty of Earth Sciences, China University of Geosciences (WUHAN)*
YAN HaoJing	*Department of Physics and Astronomy, University of Missouri-Columbia*
ZHANG ShuangNan	*Institute of High Energy Physics, Chinese Academy of Sciences*
ZHANG SiJiong	*Nanjing Institute of Astronomical Optics and Technology, Chinese Academy of Sciences*
ZHOU YouYuan	*National Astronomical Observatories, Chinese Academy of Sciences*
ZHU Zi	*School of Astronomy and Space Science, Nanjing University*
ZOU ZhenLong	*National Astronomical Observatories, Chinese Academy of Sciences*

Editorial Office

Editorial Director HUANG YanHong

Editorial Staffs GUO YuanYuan HOU XiuZhou WANG Wei | **Cover designer** HU Yu

Address: 16 Donghuangchenggen North Street, Beijing 100717, China

Tel: +86-10-64015835 | **Fax:** +86-10-64016350 | **Email:** physics@scichina.org

SCIENCE CHINA
Physics, Mechanics & Astronomy

• Article •

October 2015 Vol. 58 No. 10: 104201
doi: 10.1007/s11433-015-5718-z

Experimental study of balanced optical homodyne and heterodyne detection by controlling sideband modulation†

LI Wei[1], YU XuDong[1], MENG ZengMing[1], JIN YuanBin[1] & ZHANG Jing[1,2*]

[1]*State Key Laboratory of Quantum Optics and Quantum Optics Devices, Institute of Opto-Electronics, Shanxi University, Taiyuan 030006, China;*
[2]*Synergetic Innovation Center of Quantum Information and Quantum Physics, University of Science and Technology of China, Hefei 230026, China*

Received June 6, 2015; accepted August 3, 2015

We experimentally study optical homodyne and heterodyne detections with the same setup, which is flexible to manipulate the signal sideband modulation. When the modulation only generates a single signal sideband, the light field measurement by mixing the single sideband at $\omega_0 \pm \Omega$ with a strong local oscillator at the carrier frequency ω_0 on a beam splitter becomes balanced heterodyne detection. When two signal sidebands at $\omega_0 \pm \Omega$ are generated and the relative phase of the two sidebands is locked, this measurement corresponds to optical balanced homodyne detection. With this setup, we may confirm directly that the signal-to-noise ratio with heterodyne detection is two-fold worse than that with homodyne detection. This work will have important applications in quantum state measurement and quantum information.

homodyne detection, heterodyne detection, sideband modulation, the signal-to-noise ratio

PACS number(s): 01.50.Pa, 03.65.Ta, 42.50.Lc

Citation: Li W, Yu X D, Meng Z M, et al. Experimental study of balanced optical homodyne and heterodyne detection by controlling sideband modulation. Sci China-Phys Mech Astron, 2015, 58: 104201, doi: 10.1007/s11433-015-5718-z

1 Introduction

Optical homodyne and heterodyne detections are the extremely useful and flexible measuring methods and have broad applications in optical communication [1,2], weak signal detection [3]. In general, optical homodyne and heterodyne detections are defined as the difference of the optical frequencies of the two mixed field is zero and nonzero respectively. When the signal is mixed with a relative strong local oscillator (LO) on a 50% beam splitter, the two output modes are detected by a pair of detectors and the difference of two photocurrents can be measured, this scheme corresponds to balanced homodyne and heterodyne detections. It is well known that balanced detection can cancel the noise resulting from local oscillator [4,5]. Balanced homodyne detection is phase sensitive and has been intensively utilized to measure non-classical states of light [6–10] and further in quantum information experiments [11–14]. Heterodyne detection has been shown that its signal-to-noise ratio is two-fold worse than that with homodyne detection [4,5,15,16].

In this paper, we use sideband method [17,18] in quantum optics to investigate balanced homodyne and heterodyne detections in the same setup. When only mixing the single sideband signal at $\omega_0 \pm \Omega$ with a strong LO at the carrier frequency ω_0 on a 50% beam splitter, this measurement corresponds to balanced heterodyne detection. When there are two signal sidebands at $\omega_0 \pm \Omega$ and the relative phase of the two sidebands is locked, this measurement corresponds to balanced homodyne detection. Although the frequencies of two sidebands are different with that of LO, it still refers as balanced homodyne detection since two sidebands locate symmetrically at the two sides of the carrier frequency of

*Corresponding author (email: jzhang74@sxu.edu.cn)
†Contributed by ZHANG Jing (Associated Editor)

© Science China Press and Springer-Verlag Berlin Heidelberg 2015

LO, and at the same time the relative phase of two sidebands is fixed. This balanced homodyne detection for two sidebands has been exploited widely in quantum optics experiments [6–8,19,20]. We will demonstrate that this balanced homodyne detection is also phase-sensitive and its signal-to-noise ratio is two-fold better than that with heterodyne detection. This work gives the deeper understanding of optical homodyne and heterodyne detections and the closely relationship between them. Moreover, the scheme of generating two sidebands in this paper is different from the general method of phase-modulation (or amplitude-modulation) by an electro-optic modulator (EOM). A laser with frequency ω_0 is phase-modulated (or amplitude-modulated) by EOM with frequency Ω to generate two sidebands $\omega_0 \pm \Omega$, hence, this light includes a strong carrier field and two sidebands. The signal field in this work only has two sidebands and the optical field at carrier frequency ω_0 is vacuum, which will have the special applications in quantum information and communication.

2 Experimental setup and results

Figure 1 shows the experimental setup. A continuous-wave single-frequency coherent laser at 1064 nm is split into two parts. One passes through a mode clean cavity to be used for the LO in the balanced detection system. The other is sent through three acousto-optic modulators (AOMs, 3110-197, Crystal Technology) for generating signal sidebands. The laser first is frequency down-shifted by the negative first-order diffraction of AOM1 with the frequency –110 MHz. Then the downshifted laser is split into two beams, which are frequency up-shifted by the positive first-order diffraction of AOM2 with +115 MHz and AOM3 with +105 MHz, respectively. The two frequency-shifted beams are combined on 50% BS1 with the same polarization, so the two sidebands at $\Omega_{+(-)} = 5$ MHz is generated. Here, the sinusoidal signals of AOMs are provided by three signal generators (N9310A, Agilent) respectively and the diffraction efficiency of all AOMs are about 70%. The two-sideband field is coupled into a single-mode polarization-maintaining fiber and then combined with a strong local oscillator on 50% BS2 with the same polarization. The output fields of BS2 are detected by two balanced detectors, the substraction of whose photocurrents is measured by the spectrum analyzer. The single sideband can be obtained by blocking the incident beam of AOM2 (or AOM3). Here, an auxiliary beam without frequency shift is used to adjust the visibility of the interference between the local and the signal. When the data is measured, the auxiliary beam will be blocked.

The difference photocurrent of the balanced detection can be expressed as:

$$\delta i = i_1 - i_2 = a_{\mathrm{LO}}^{\dagger} a_{\mathrm{s}} + a_{\mathrm{LO}} a_{\mathrm{s}}^{\dagger}. \quad (1)$$

The LO field can be written as $a_{\mathrm{LO}} = \langle a_{\mathrm{LO}} \rangle \mathrm{e}^{\mathrm{i}(\omega_0 t+\theta)}$, and the signal field as $a_{\mathrm{s}} = \langle a_+ \rangle \mathrm{e}^{\mathrm{i}(\omega_0+\Omega_+)t} + \langle a_- \rangle \mathrm{e}^{\mathrm{i}(\omega_0-\Omega_-)t}$, which includes two sidebands. Here, θ is the relative phase between the LO and signal field. Hence, the photocurrent of the signal field is written as:

$$\delta i_{\mathrm{s}} = 2\langle a_{\mathrm{LO}} \rangle [\langle a_+ \rangle \cos(\Omega_+ t - \theta) + \langle a_- \rangle \cos(\Omega_- t + \theta)]. \quad (2)$$

Here, two terms represent the two beatnotes of the two sidebands with LO, respectively. Case 1: When only one signal sideband is applied (a_+ or a_-), the signal strength becomes $(2\langle a_{\mathrm{LO}} \rangle \langle a_{\mathrm{s}} \rangle)^2$ at the frequency of Ω_{s}, where $\langle a_{\mathrm{s}} \rangle = \langle a_{+(-)} \rangle$ and $\Omega_{\mathrm{s}} = \Omega_{+(-)}$. We can see that the signal strength becomes constant and is independent of the relative phase θ between the LO and signal field for single signal sideband, as shown in Figure 2 (red line). This case corresponds to balanced heterodyne detection. Case 2: When two signal sidebands are applied at the same time and have the same amplitude with $\langle a_{\mathrm{s}} \rangle = \langle a_+ \rangle = \langle a_- \rangle$, the difference of photocurrent can be written as:

$$\delta i_{\mathrm{s}} = 2\langle a_{\mathrm{LO}} \rangle \langle a_{\mathrm{s}} \rangle \cos\left(\frac{\Omega_+ - \Omega_-}{2} t - \theta\right) \cos\left(\frac{\Omega_+ + \Omega_-}{2} t\right). \quad (3)$$

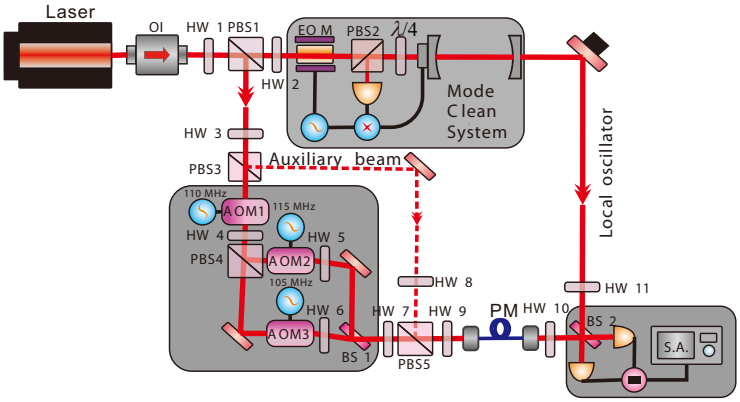


Figure 1 (Color online) Schematic diagram of the experimental setup. OI: optical isolator; HW: half-wave plate; PBS: polarizing beam splitter; AOM: acousto-optic modulator; PM: single-mode polarization-maintaining fiber; EOM: electro-optic modulator; SA: spectrum analyzer.

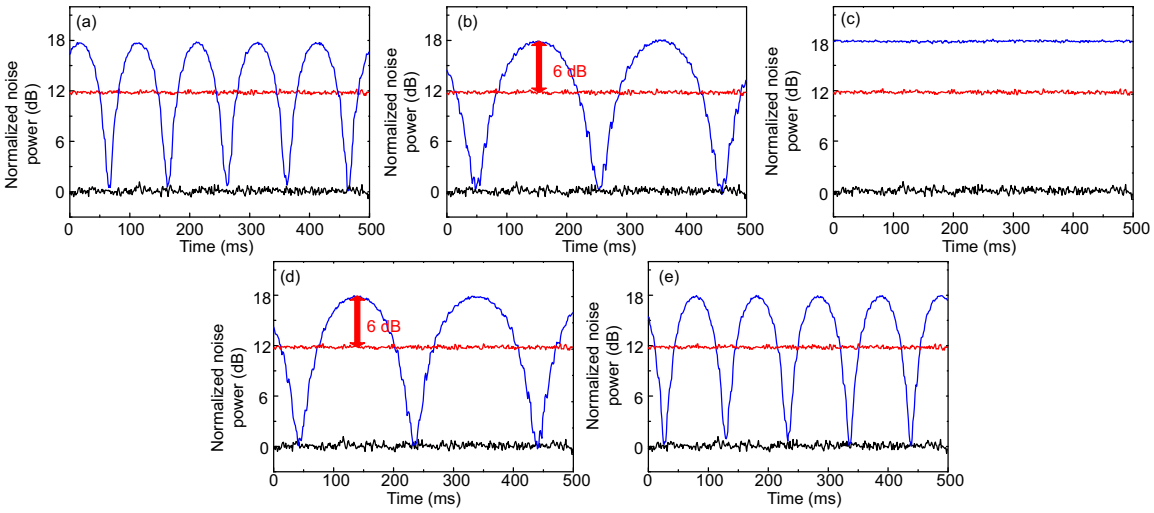


Figure 2 (Color online) The measured noise spectra of the signal beam by the balanced detection system. The modulation frequency of AOM1 and AOM2 is fixed at 110 and 115 MHz, respectively, which corresponds to up sideband frequency Ω_+ =5 MHz. The frequency of AOM3 is changed to set the down sideband frequency Ω_-. The black line is the shot noise limit and the red line corresponds to the single sideband. The blue lines in (a–e) correspond to the two sidebands cases with the different frequency difference of up and down sideband $\Delta\Omega_\pm = \Omega_+ - \Omega_-$: –10, –5, 0 Hz (with θ = 0), +5, +10 Hz, respectively. The center frequency of the spectrum analyzer is 5 MHz and the span is zero. RBW is 100 kHz, VBW is 300 Hz and the sweep time is 500 ms. Here, the frequency difference of up and down sideband $\Delta\Omega_\pm$ is much less than the RBW and VBW.

The signal strength measured by spectrum analyzer becomes $4(2\langle a_{\rm LO}\rangle\langle a_{\rm s}\rangle)^2\cos^2[(\Omega_+ - \Omega_-)t/2 - \theta]$ at the frequency of $(\Omega_+ + \Omega_-)/2$. Compared with the single signal sideband, there are several new characteristics (blue line in Figures 2(a), (b), (d) and (e). First, the signal strength has a periodical modulation with the frequency $\Delta\Omega_\pm = \Omega_+ - \Omega_-$. Second, the maximum signal strength for two signal sidebands is four-fold larger than that for single signal sideband. The minimum signal strength reaches the shot noise limit. When the difference of the frequencies of two signal sidebands is zero ($\Delta\Omega_\pm = 0$), the signal strength becomes $4(2\langle a_{\rm LO}\rangle\langle a_{\rm s}\rangle)^2\cos^2(\theta)$. Here, the relative phase θ may be the relative phase between up and down sidebands or between the LO and signal field. When the relative phase between up and down sidebands is fixed, this case corresponds to balanced homodyne detection, which is phase sensitive to the relative phase θ between the LO and signal field. When the relative phase θ is zero, the signal strength reaches the maximum value (blue line in Figure 2(c)), which corresponds the constructive inference of two sidebands. When the relative phase θ is $\frac{\pi}{2}$, the signal strength becomes zero (shot noise level), which corresponds the destructive inference of two sidebands.

As above discussion, only when the two signal sideband frequencies $\Omega_{+(-)}$ are the same and the relative phase is fixed, the measurement becomes the balanced homodyne detection. Here we develop two methods to lock the relative phase between up and down sidebands.

Method 1. Figure 3 shows the schematic diagram of locking the relative phase between up and down sidebands. The sinusoidal signal output of the signal generator 1 is divided into two parts: one is used to drive the AOM1 and the other is further divided into two parts to mix with the output of the signal generators 2 and 3. The sinusoidal signal output of the signal generator 2 (3) is also divided into two parts: one is used to drive the AOM2 (AOM3) and the other is to mix with the output of the signal generator 1. Two sinusoidal signals from the signal generators 1 and 2 (1 and 3) are mixed down to generate about 5 MHz signal using a mixer (Mini-Circuits ZAD-6+). The mixer's output signal of about 5 MHz pass through a low-pass in order to filter the high frequency signals of the inputs of the mixer. Thus we obtain two ways of 5 MHz signal, which correspond to two sideband frequencies Ω_+ and Ω_- respectively. Two ways of 5 MHz signal are electronically phase-locked to the same 5 MHz reference signal by two phase locked loops (PLL). The output error signal of

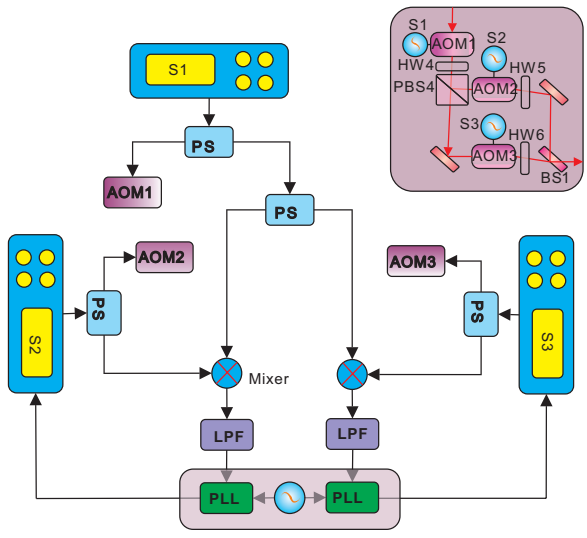


Figure 3 (Color online) The schematic diagram of the method 1 for locking the relative frequency and phase of the two sidebands. S1-3: signal generator; PS: power splitter; AOM: acousto-optic modulator; LPF: low-pass filter; PLL: phase locked loop.

the PLL contains the relevant information abut the frequency and phase difference between two input signals. Two ways of the error signal, after the proportional-integral-derivative controller, are feedback into the signal generators 2 and 3, respectively. When the frequency are same and the relative phase between up and down sidebands is locked, the optical field with two signal sidebands can be phase-sensitively detected by the balanced homodyne detection.

By controlling the phase of the LO, the relative phase θ between the LO and signal field can be fixed with zero and the signal strength reaches the maximum value (blue line in Figure 4(a)). When the relative phase θ is fixed at $\pi/2$, the signal strength becomes zero and reaches the shot noise level (pink line in Figure 4(a)). This pink line presents the large fluctuation due to imperfect locking. When we scan the phase of LO field, the signal strength presents a periodical change (green line in Figure 4(a)).

Method 2. Here, in Figure 5 we present a simpler scheme to make the frequencies and the relative phase of the up and down sidebands locked by using the clock synchronization of Agilent signal generators. The three signal generators can be locked together in frequency and phase by using the same reference (clock) frequency. So the sinusoidal signal outputs are generated from the same clock source. For instance, the signal generator 1 serves as the master reference, whose signal first is locked with its internal reference. The reference output of the signal generator 1 is connected with the external reference input of the signal generators 2 and 3. The signals of the signal generators 2 and 3 are locked with the external reference. The result of the balanced homodyne detection is shown in Figure 4(b), which is better than that with the method 1.

We further measure the noise spectra with the frequency span of 3 MHz when locking the frequency and phase of the two sidebands with method 2. The red line in Figure 6 presents the case of one signal sideband, which corresponds to balanced heterodyne detection. The signal-to-noise ratio for one signal sideband is 12 dB, which is independent of the relative phase θ between the LO and signal field for single signal sideband. When two signal sidebands are applied and the phase of the two sidebands is locked, the signal-to-noise ratio is sensitive to the relative phase θ between the LO and signal field for two signal sidebands, which corresponds to balanced homodyne detection. The maximum signal-to-noise ratio for two signal sidebands is four-fold (6 dB) larger than that for single signal sideband when the relative phase $\theta = 0$. When consider the factor 2 of two sideband signals compared with single sideband, we confirm that the signal-to-noise ratio with heterodyne detection is two-fold worse than that with homodyne detection. The signal-to-noise ratio for two signal sidebands reaches zero when the relative phase $\theta = \pi/2$.

3 Conclusion

In conclusion, we experimentally study optical balanced homodyne and heterodyne detections by the sideband method. The single sideband and two sidebands signals can be obtained easily in our experimental setup, therefore optical balanced homodyne and heterodyne detections can be investigated and compared simultaneously. We also develop two methods to lock the relative phase between up and down sidebands for realizing the balanced homodyne detection. We confirm that this balanced homodyne detection scheme is phase-sensitive and its signal-to-noise ratio is two-fold bet-

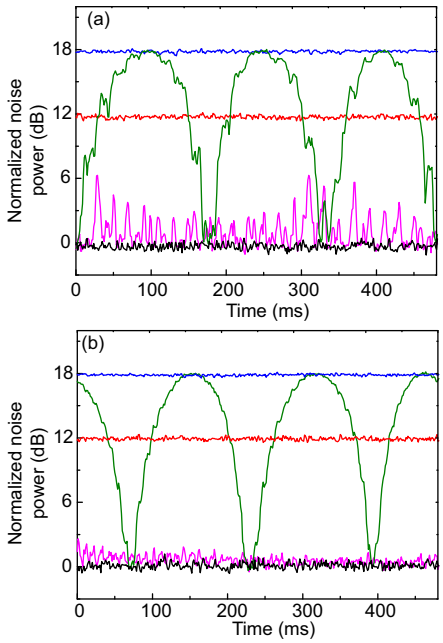


Figure 4 (Color online) The noise spectra measured after locking the frequency and phase of the two sidebands with two different methods. (a) Use method 1; (b) use method 2. The red curve shows the noise spectra of single sideband. The blue and purple curves are for the relative phase θ between the LO and signal field with zero and $\pi/2$, respectively. The green curve shows the noise spectra of two sidebands while scanning the relative phase θ between the LO and signal field. RBW=100 kHz, VBW=300 Hz, Sweep time=500 ms.

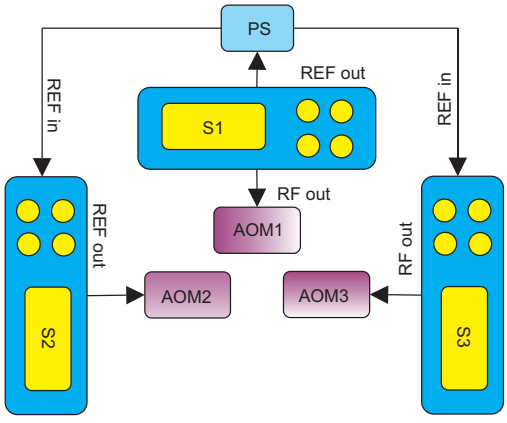


Figure 5 (Color online) The schematic diagram of the method 2 for locking the relative frequency and phase of the two sidebands. S1-3: signal source; PS: power splitter; AOM: acousto-optic modulator.

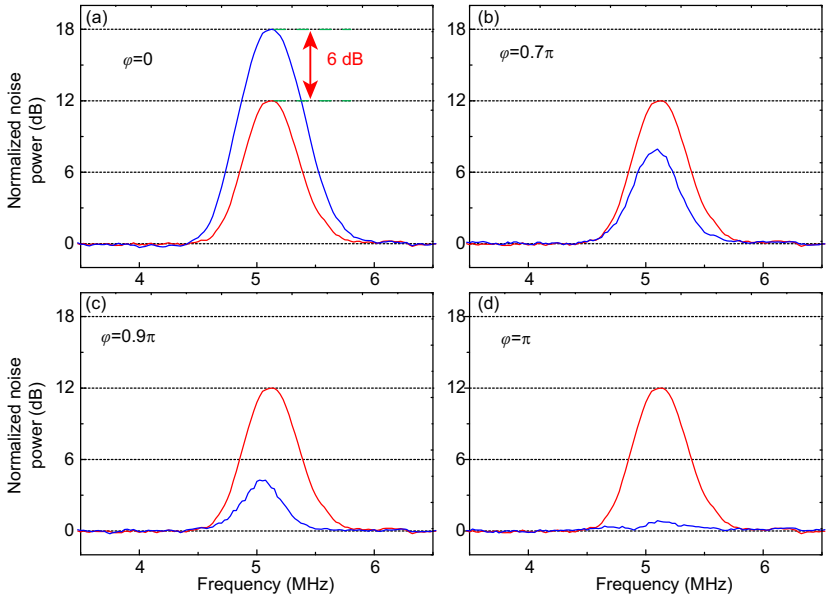


Figure 6 (Color online) The noise spectra with a certain span at the analyzed frequency when the relative frequency and phase of the two sidebands are locked. The red curves and the blue curves represent single sideband and the double sidebands cases, respectively. The span of the measured frequency is from 3.5 MHz to 6.5 MHz. RBW=100 kHz, VBW=30 Hz, Sweep time=500 ms.

ter than that with heterodyne detection. The scheme of generating single and two sideband signal in this work can be used in the quantum information and quantum metrology [21–23]. Resently, we noticed an interesting work where the heterodyne detection with a bichromatic local oscillator was theoretically and experimentally studied [24].

This work was supported by the National Basic Research Program of China (Grant No. 2011CB921601), the National Natural Science Foundation of China (Grant Nos. 10725416 and 60821004).

1 Okoshi T, Kikuchi K. Coherent Optical Fiber Communications. Tokyo: Dordrecht; Boston by KTK Scientific Publishers; Kluwer Academic Publishers, 1988
2 Su X L. Applying Gaussian quantum discord to quantum key distribution. Chin Sci Bull, 2014, 59: 1083–1090
3 Martellucci S, Chester A N, Mignani A G. Optical sensors and microsystems: New concepts, materials, technologies. Boston: Kluwer Academic Publishers, 2002
4 Yuen H P, Chan V W S. Noise in homodyne and heterodyne detection. Opt Lett, 1983, 8: 177–179
5 Collett M J, Loudon R, Gardiner C W. Quantum theory of optical homodyne and heterodyne detection. J Mod Opt, 1987, 34: 881–902
6 Wu L A, Kimble H J, Hall J L, et al. Generation of squeezed states by parametric down conversion. Phys Rev Lett, 1986, 57: 2520–2523
7 Yu X D, Li W, Jin Y B, et al. Experimental measurement of covariance matrix of two-mode entangled state. Sci China-Phys Mech Astron, 2014, 57: 875–879
8 Su X L, Jia X J, Xie C D, et al. Preparation of multipartite entangled states used for quantum information networks. Sci China-Phys Mech Astron, 2014, 57: 1210–1217
9 Breitenbach G, Schiller S, Mlynek J. Measurement of the quantum states of squeezed light. Nature, 1997, 387: 471–475
10 Su X L, Jia X J, Xie C D, et al. Generation of GHZ-like and cluster-like quadripartite entangled states for continuous variable using a set of quadrature squeezed states. Sci China-Phys Mech Astron, 2008, 51: 1–13
11 Furusawa A, Sørensen J L, Braunstein S L, et al. Unconditional quantum teleportation. Science, 1998, 282: 706–709
12 Grosshans F, Van Assche G, Wenger J, et al. Quantum key distribution using gaussian-modulated coherent states. Nature, 2003, 421: 238–241
13 Braunstein S L, Loock P van. Quantum information with continuous variables. Rev Mod Phys, 2005, 77: 513–577
14 Xie D, Peng J Y. Accuracy for superposition of squeezed states in lossless and dissipative channel. Sci China-Phys Mech Astron, 2013, 56: 593–599; Dugić M, Arsenijević M, Jeknić-Dugić J. Quantum correlations relativity for continuous variable systems. Sci China-Phys Mech Astron, 2013, 56: 732–736
15 Yamamoto Y, Haus H A. Preparation, measurement and information capacity of optical quantum states. Rev Mod Phys, 1986, 58: 1001–1020
16 Caves C M, Drummond P D. Quantum limits on bosonic communication rates. Rev Mod Phys, 1994, 66: 481–537
17 Bachor H A. A Guide to Experiments in Quantum Optics. Weinheim: Wiley/VCH, 1998
18 Zhang J. Einstein-Podolsky-Rosen sideband entanglement in broadband squeezed light. Phys Rev A, 2003, 67: 054302
19 Di K, Yu X D, Zhang J. Experimental investigation of small-sized squeezed vacuum light device. Acta Sin Quantum Opt, 2010, 16: 241–246
20 Su X L, Hao S H, Deng X, et al. Gate sequence for continuous variable one-way quantum computation. Nat Commun, 2013, 4: 2828
21 Wheatley T A, Berry D W, Yonezawa H, et al. Adaptive optical phase estimation using time-symmetric quantum smoothing. Phys Rev Lett, 2010, 104: 093601
22 Yonezawa H, Nakane D, Wheatley T A, et al. Quantum-enhanced optical-phase tracking. Science, 2012, 337: 1514–1517
23 Zhai Z H, Gao J R. Low-frequency phase measurement with high-frequency squeezing. Opt Express, 2012, 20: 18173–18179
24 Fan H, He D, Feng S. Quantum noise in phase-sensitive heterodyne detection with a bichromatic local oscillator. arXiv: 1410.8602

Information for authors

SCIENCE CHINA Physics, *Mechanics & Astronomy*, a monthly peer-reviewed academic journal cosponsored by the Chinese Academy of Sciences and the National Natural Science Foundation of China, and published by Science China Press and Springer, is committed to publishing high-quality, innovative results of broad interests in both basic and applied research.

Categories of articles:

Reviews: summarize representative results and achievements in a particular topic or an area, comment on the current state of research, and advise on the research directions. The author's own opinion and related discussion are requested.

Articles: report on important original results in all areas of physics, mechanics and astronomy.

Letters: present short reports in a timely manner of the latest important results.

Research Highlights: are succinct summaries and comments on a recent research achievement published in SCPMA and other journals.

Authors are recommended to use the online submission services. To submit a manuscript, please visit phys.scichina.com, click the button "submission", and use ScholarOne Manuscripts. For a new user, please register an "Author Accoant", and then submite a manuscript following the guidance.

Authors should also submit such accompanying materials as a short statement on the research background and significance of the work, a brief introduction to the first and corresponding authors including their mailing address, post code, telephone number, fax number, and email address. Authors may suggest several referees (please supply full names, addresses, phone, fax and email), and/or request the exclusion of specific reviewers.

All submissions will be reviewed by referees selected by the editorial board. The decision of acceptance or rejection of a manuscript is made by the editorial board based on the referees' reports. The entire review process may take 30 to 90 days, and the editorial office will inform the author of the decision as soon as the process is completed. If the editorial board fails to make a decision within 90 days, please contact the editorial office.

Authors should guarantee that their submitted manuscript has not been published before, and has not been submitted elsewhere for print or electronic publication consideration.

Submission of a manuscript is taken to imply that all the named authors are aware that they are listed as co-authors, and they have seen and agreed to the submitted version of the paper. No change in the order of listed authors can be made without an agreement signed by all the authors.

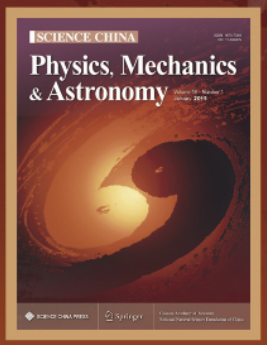
Once a manuscript is accepted, the authors should send a copyright transfer form signed by all authors to Science China Press. Authors of each published paper will be presented one sample copy. If more sample copies and offprints are required, please contact the managing editor and pay the extra fee. The full text in Chinese and in English opens free to the readers in China at phys.scichina.com, and the full text in English is available to overseas readers at link.springer.com.

Ethical responsibilities of authors: Authors should refrain from misrepresenting research results which could damage the trust in the journal and ultimately the entire scientific endeavour, and follow the COPE guidelines on how to deal with potential acts of misconduct.

Disclosure of potential conflict of interests: Authors must disclose all relationships or interests that could influence or bias the work. The corresponding author will include a summary statement in the text of the manuscript in a separate section before the reference list.

Subscription information

ISSN print edition: 1674-7348
ISSN electronic edition: 1869-1927
Volume 58 (12 issues) will appear in 2015
Subscription rates
For information on subscription rates please contact:
Customer Service
China: sales@scichina.org
North and South America:
journals-ny@springer.com
Outside North and South America:
subscriptions@springer.com
Orders and inquiries:
China
Science China Press
16 Donghuangchenggen North Street, Beijing 100717, China
Tel: +86 10 64019709 or +86 10 64015835
Fax: +86 10 64016350
North and South America
Springer New York, Inc.
Journal Fulfillment, P.O. Box 2485
Secaucus, NJ 07096 USA
Tel: 1-800-SPRINGER or 1-201-348-4033
Fax: 1-201-348-4505
Email: journals-ny@springer.com
Outside North and South America:
Springer Distribution Center
Customer Service Journals
Haberstr. 7, 69126 Heidelberg, Germany
Tel: +49-6221-345-0, Fax: +49-6221-345-4229
Email: subscriptions@springer.com
Cancellations must be received by September 30 to take effect at the end of the same year.
Changes of address: Allow for six weeks for all changes to become effective. All communications should include both old and new addresses (with postal codes) and should be accompanied by a mailing label from a recent issue. According to § 4 Sect. 3 of the German Postal Services Data Protection Regulations, if a subscriber's address changes, the German Federal Post Office can inform the publisher of the new address even if the subscriber has not submitted a formal application for mail to be forwarded. Subscribers not in agreement with this procedure may send a written complaint to Customer Service Journals, Karin Tiks, within 14 days of publication of this issue.
Microform editions are available from: ProQuest. Further information available at http://www.il.proquest.com/uni
Electronic edition
An electronic version is available at link.springer.com
Production
Science China Press
16 Donghuangchenggen North Street, Beijing 100717, China
Tel: +86 10 64019709 or +86 10 64015835
Fax: +86 10 64016350
Printed in the People's Republic of China
Jointly published by
Science China Press and Springer



SCIENCE CHINA
Physics, Mechanics & Astronomy

(Formerly *Science in China Series G: Physics, Mechanics & Astronomy*)

ABOUT THE JOURNAL

SCIENCE CHINA Physics, Mechanics & Astronomy (Sci China-Phys Mech Astron) is a monthly peer-reviewed research journal, founded in 2003, that is devoted to the publication of the basic and innovative research results of high quality and broad interest in the fields of physics, mechanics and astronomy.

NOW INDEXED IN

SCI, EI, ADS, Google Scholar, INSPEC, etc.

SUBMISSION

Visit the website of http://phys.scichina.com, click the button "submission and review", and use "ScholarOne Manuscripts".

MANUSCRIPT TYPES

Reviews: summarize representative results and achievements in a particular topic or an area.

Articles: report on important original results in all areas of physics, mechanics and astronomy.

Letters: present short reports in a timely manner of the latest important results.

Research Highlights: are succinct summaries and comments on a recent research achievement published in SCPMA and other journals.

ALL ARTICLES AVAILABLE ONLINE

All articles are available online through http://phys.scichina.com and http://www.springer.com/scp

FREE

Read freely for domestic users by http://phys.scichina.com

ADVERTISING SERVICES

Institutional ads, Product ads, Information ads, Recruitment ads

Position	Inside Front Cover (Cover 2)	Inside Back Cover (Cover 3)	Back Cover (Cover 4)	After Cover 2	Before Cover 3	Inside Page
Price RMB / Issue	10,000	8,000	12,000	8,000	6,000	5,000

Sponsored by
Chinese Academy of Sciences (CAS)
National Natural Science Foundation of China (NSFC)

Published by
Science China Press & Springer

ISSN 1674-7348