

# 邓锡铭

## 研究论文集

COLLECTION OF THESES

1961-2000

中卷

中国科学院  
中国工程物理研究院

高功率激光物理联合实验室

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# 目 录

## 上 册

光学量子放大器 .....	1
激光器 .....	6
激光 .....	14
回顾——纪念长春光机所建所三十周年 .....	21
纪念激光器发明 30 周年 .....	26
激光应用的回顾与展望 .....	31
高功率激光研究二十年 .....	34
激光核聚变国内外概况(上) .....	41
激光核聚变国内外概况(下) .....	48
激光与核聚变 .....	54
高功率激光与激光核聚变 .....	56
我国激光的早期发展(1960~1964) .....	59
高功率激光与“神光”装置 .....	63
近代科技和信息化 .....	69
对超临界振荡过程的若干分析 .....	73
氦氖混合气体受激光发射器 .....	77
负吸收介质法卜利-白洛干涉仪 .....	79
利用 Fabry-Perot 干涉器改善受激光发射器的波型选择特性 .....	82
锌原子串级非弹性碰撞截面 .....	90
长间隔光学谐振腔波型之间的拍频 .....	97
气体受激光发射器的波形分离 .....	99
激光振荡的生成时间 .....	101
扭镜对提高钕玻璃激光器性能的作用 .....	103
激光束的运动方式对钕玻璃破坏阈值的影响 .....	108
间断脉冲放大器 .....	113
多台组合振荡器 .....	119
大功率激光行波放大器的总体排布 .....	123

在真空中电磁场的梯度矢势 .....	124
在真空中电磁场的整体运动和内部运动 .....	134
用于核聚变研究的大功率激光系统的发展 .....	140
激光等离子体相互作用和靶压缩研究 .....	141
电子的整体运动和内部运动 .....	142
成像法测量空心玻璃微球壁厚 .....	147
电磁场的梯度矢势与玻姆量子势 .....	150
计算光束衍射传输的一种新方法 .....	154
六束亚毫微秒高功率钕玻璃激光系统 .....	159
傍轴光束传输的动力学分析 .....	169
测量光学系统焦平面能量分布的一种方法 .....	179
光束通过硬边光阑的内禀能量和衍射发散度 .....	184
A long pulse width neodymium-doped glass rod laser amplifier with a moving input laser beam .....	187
Waist position of a paraxial light beam .....	192
Development of high-power laser system for laser-fusion research .....	198
Development of high-power laser system for laser-fusion research in the people's republic of china .....	202
激光辐照平面靶产生的二次谐波结构 .....	211
用增加频带宽度的方法提高钕玻璃高功率激光器输出功率的建议 .....	216
激光等离子体的共振吸收对二次谐波的时间分辨谱及时间积分谱的影响 .....	217
用增加频带宽度的方法提高钕玻璃高功率激光器输出功率 .....	218
傍轴光束截面的内能是一个不变量 .....	223
用透镜阵精确测大口径激光束的波前曲率 .....	229
扭动光束钕玻璃棒状激光放大器 .....	233
遥控脉冲激光多普勒测速仪 .....	236
Effect of resonant absorption of laser-induced plasma on temporal resolved spectrum and temporal integrated spectrum .....	239
Intrinsic angular momentum of the electromagnetic field .....	246
统一表述谐振腔共振条件的一个公式 .....	264
激光陀螺拍频公式的修正 .....	268
窄频带及宽频带激光束的传输特性 .....	271
光束在缓变折射率介质中的传输 .....	276
Correction to the beat frequency for laser gyroscopes .....	283
用透镜列阵实现大焦斑面的均匀照射 .....	285
激光等离子体慢离子发射波形的双峰结构 .....	289

The effect of bandwidth on the absorption of laser plasma ..... 296

Uniform illumination of large targets using ma lens array ..... 302

对撞脉冲锁模磷酸盐钕玻璃激光器 ..... 307

用透镜阵聚焦实现均匀辐照的计算机分析 ..... 308

光学共振反射器及其在激光技术中的应用 ..... 314

对撞脉冲锁模 Nd:YAG 激光器的若干运转特性 ..... 320

大曲率半径球形光学列阵成像质量的方和裴衍射分析 ..... 326

用于激光核聚变的可长时间单纵模稳定运转的 Nd:YAG 和 Nd:YLF 激光振荡器的研究  
..... 333

瞬态同步泵浦锁模若丹明染料激光的模拟分析及相应实验结果 ..... 340

激光平面靶  $3\omega_0/2$  谐波空间精细结构的时间和光谱特性 ..... 347

激光等离子体  $3\omega_0/2$  谐波的时间、空间分辨与密度轮廓分布 ..... 354

Resonance absorption initiated by self-focusing filamentation ..... 361

Temporal and spectral features of the  $(3/2)\omega_0$  spatial fine structure in laser irradiated  
planar targets ..... 368

激光等离子体电子密度分布的测量 ..... 376

泵浦光偏振方向和溶剂粘滞性对同步泵浦锁模染料激光脉宽的影响 ..... 383

The space and time resolved structures of the  $(3/2)\omega_0$  harmonic and density profile  
in laser plasmas ..... 386

激光等离子体二次谐波时间分辨光谱的细结构 ..... 394

激光频带宽度对二次谐波时空分辨结构的影响 ..... 399

The influence of laser frequency bandwidth on the time and space resolved structures  
of the  $2\omega_0$  harmonic generation ..... 407

The fine structure of the  $2\omega_0$  time resolved spectrum in laser plasmas ..... 412

激光加热微管靶得到很高的粒子数反转 ..... 418

瞬态同步泵浦锁模腔长负失谐现象的观察 ..... 419

Fast-ion spectrum emitted from laser plasmas ..... 422

三片光学共振反射器及其设计中的若干问题 ..... 430

激光等离子体的快离子发射谱 ..... 437

中 册

Evidence, From space resolved spectra, of  $2\omega_0$  harmonic generation in laser irradiated  
plasma filaments ..... 445

The mechanism for the second harmonic generation in laser irradiated microtube targets .....	451
Dynamical behaviour of two-wave coupling in undoped GaAs on a picosecond time scale .....	455
A new target configuration producing an effective population inversion at energy levels of MgXI 1s3p and 1s4p .....	458
激光加热微管靶在软 X 射线波段观察很高的粒子数反转 .....	465
机械转镜隔离器 .....	472
MgXI 1s3p-1s4p 能级间平均高温及高密度条件下的粒子数反转 .....	477
激光加热微管靶反激光方向二次谐波时空分辨结构 .....	485
饱和吸收体腔内压缩瞬态同步泵浦锁模光脉冲 .....	490
Finite beam width optics .....	495
High population inversion in the soft-x-ray band observed in a laserirradiated microtube .....	500
被动锁模涨落脉冲数和第二阈值研究 .....	504
微管靶等离子体电子温度密度的空间分布 .....	511
机械转镜隔离器的光束位置复原特性研究 .....	515
磷玻璃宽带调 Q 激光器 .....	520
激光加速器中电子能量增益的广义协变推导 .....	526
实现激光核聚变的一种新方案 .....	534
ABCD 定律的推广 .....	535
利用非共线二次谐波的产生测量 ps 光脉冲的形状和宽度 .....	543
电磁场的内禀角动量 .....	548
超短腔染料激光器时间特性的研究 .....	561
简并四波混频用于饱和吸收体的性能比较 .....	564
一级放大的超短腔染料激光器 .....	568
中皮秒二波耦合及其应用 .....	571
宽频带掺钕硅玻璃调 Q 振荡器 .....	576
GaAs 中瞬态二波耦合及其光的偏振——一种实现红外 ps 光开关的新途径 .....	582
A generally covariant derivation of the energy gain of electrons in a laser accelerator .....	586
Thermal coupling of pulsed 0.53- $\mu$ m laser radiation to aluminums in air .....	594
长短脉冲振荡器同步输出的研究 .....	596
一种新的锁模技术 .....	601
Gallium arsenide: A new material to accomplish passively mode-locked Nd:YAG laser .....	603

正反馈选模和调 Q 技术 .....	606
Temporal reshaping of Q-switched pulse by using two-photon absorption .....	611
A novel mode-selecting and Q-switching technique .....	616
高功率激光聚集均匀照明靶面的验证 .....	620
光电导控制激光器锁模、选频、调 Q 和同步 .....	625
Near diffraction limit output and gain saturation of soft X-ray laser .....	631
Temporal shaping of single-longitudinal Q-switched pulses by means of two-photon absorption in an external cavity .....	635
HMO model of scalar field in medium and self-focusing .....	639
光在线性介质中的度规描述 .....	644
HMO model of scalar field in vacuum .....	648
Colliding pulse mode-locked Nd:YLF laser with negative feedback control by GaAs photoconductive switch .....	651
复合折射棱镜的色散研究 .....	655
无衍射发散光束的判据 .....	660
Intrinsic angular momentum in HMO .....	662
Dynamic analysis of optical fluid in medium .....	668
LD 泵浦的 Nd:YAG 微片激光器实验研究 .....	675
高能量、长锁模脉冲序列的 Nd:YLF 激光器研究 .....	680
稳态锁模产生 4ps 激光脉冲 .....	683
Nd:YLA 激光器中以负反馈强迫的自锁模技术 .....	687
HMO in geometrical optics .....	691
HMO in nonlinear optics .....	695
可变焦列阵柱面透镜均匀线聚焦系统 .....	700
Relativistic aspects of HMO .....	706
HMO is study on diffraction-free beams .....	710
Serrated aperture and its applications in high power lasers .....	713
Using kinoform phase plates to generate uniform focal profiles .....	716
High energy and efficient SHG by using convex-antiresonant ring unstable resonator Nd:YAP pulsed laser .....	721
Stimulated brillouin scattering(SBS) excited with a phase-modulated pump laser .....	725
用消衍射方法改善透镜列阵的辐照均匀性 .....	735
Differential geometrical methods in the study of optical transmission (scalar theory). I. Static transmission case .....	740
Differential geometrical methods in the study of optical transmission (scalar theory). II. Time-dependent transmission theory .....	747

Propagation and beam quality of flattened hermite-gauss beams .....	751
Fermat 原理及稳态光束传输的微分几何研究 .....	757
非稳态光传输的微分几何描述 .....	764
稳态光束传输的动力学分析 .....	769
啁啾脉冲受激布里渊散射的理论研究 .....	774
高功率宽频带激光的高效谐波转换及其新进展 .....	781
半导体激光纵向泵浦的光学耦合系统设计 .....	787
傍轴黎曼几何光学. I. 理论 .....	793
傍轴黎曼几何光学. II. 应用基础 .....	799
单纵模激光的再生放大 .....	806
参加惯性约束聚变驱动器国际会议情况汇报 .....	812
利用波纹光阑和空间滤波器改善光束近场分布 .....	821
Nd:YLF 单纵模调 Q 激光器腔内脉冲稳幅的实验研究 .....	825
调 Q 激光脉冲的腔内时间整形 .....	828
Active SBS mirror applied to ICF driver .....	832

## 下 册

超高斯光束的上限阶数 .....	843
光束截面角动量的轴向分量是守恒量 .....	848
一种测量光束横向尺寸的新方法 .....	853
用双折射晶体相位延迟法选纵模的理论分析和实验研究 .....	858
光束截面的动量守恒及动量衍射发散度 .....	867
LiNbO <sub>3</sub> 电光偏转器的研究 .....	872
光束截面的能量守恒及能量衍射发散度 .....	876
LiNbO <sub>3</sub> 电光偏转器的研究 .....	881
对 Fermat 原理的一个推广 .....	885
Propagation of flattened hermite-gauss beams around a thin lens .....	891
复杂激光脉冲波形的整形 .....	897
超短脉冲在远场的时空特性 .....	902
远场的薄色散介质对超短脉冲的影响 .....	906
振幅分布对焦移的影响. I. 傍轴光束 .....	910
非傍轴光束的光束质量因子. I. 定义 .....	915
非傍轴光束的光束质量因子. II. 特性分析 .....	921
傍轴黎曼几何光学. III. 光束传输的统计行为 .....	926



傍轴黎曼几何光学. IV. 两种光束质量因子 .....	933
傍轴黎曼几何光学. V. 傍轴光束的空间变换 .....	938
横截面上光强的精确表述 .....	944
三倍频激光束特性传输变换的近似模型 .....	950
用快速电光偏转器对激光脉冲削波 .....	954
电光偏转器的矩阵表示和应用 .....	958
Evanescent waves and energy conservation .....	963
The light tracks in the optical fibers with two types of parabolic refractive indices .....	968
利用电光偏转器进行激光脉冲整形的两种扫描光路的比较 .....	978
$M^2$ factor of nonparaxial vector beams .....	984
Investigation on coaxial Double-Pass main amplifier in high power laser fusion driver .....	990
利用波导调制器实现连续可调任意整形激光脉冲 .....	1000
激光远场 CCD 诊断仪 .....	1006
列阵均匀照明系统的优化设计 .....	1013
LD 端面泵浦 $\text{Cr}^{4+}:\text{YAG}$ 被动调 Q 的 Nd:YLF 激光器 .....	1017
Propagation rule of pulsed light beams through first-order optical systems .....	1021
傍轴光束在自由空间中传输的几何行为研究 .....	1027
傍轴光束在自由空间中传输的不变积分和统计行为方程 .....	1034
固体激光器的稳模式热稳条件分析 .....	1042
二极管侧面泵浦声光诱导单向运转的 Nd:YLF 环形腔激光器 .....	1051
声光诱导单向运转的 Nd:Glass 环形腔激光器 .....	1056
Invariant integral and statistical equations of paraxial light beam transmission in free space .....	1061
Laser pulsewidth compression by coherent wave mixing in silicon .....	1070
A new method for interpreting the effective radius of curvature; Two-dimensional case .....	1074
Geometrical study of paraxial light beam transmission in free space .....	1077
用单晶硅在 Nd:YAG 激光器中实现被动锁模 .....	1085
Spatial parametric characterization of general polychromatic light beams .....	1088
Short pulse generation in a Nd:YAG laser by silicon .....	1199
新型 KTP 电光偏转器的设计和分析 .....	1105
度规光学中的聚焦定理及其应用 .....	1110
利用微带传输线获取连续可调任意整形电脉冲 .....	1114

A novel feedback stable electro-optic Q-switching technique by use of a photoconductor ..... 1119

利用 LiNbO<sub>3</sub> 电光调制器实现宽频带激光输出 ..... 1120

真空中线性啁啾时空高斯脉冲传输特性的分析 ..... 1124

Corrections to the paraxial approximation of an arbitrary free-propagation beam ... 1128

Intense Nickel-like neodymium X-ray laser at 7.9nm with a Double-Curved-Slab target ..... 1133

Power carried by scalar light beams ..... 1137

A new type of reflector mount array ..... 1142

Diode end-pumped additive pulse mode locked Nd:YLF laser ..... 1150

多臂迈克耳逊干涉仪激光脉冲整形系统——I. 参数的设计 ..... 1159

傍轴黎曼几何光学应用——光束自聚焦 ..... 1164

Temporal pulse shaping of laser beams by optical-fiber stacker ..... 1170

关于衍射与无衍射光束 ..... 1174

二极管端面泵浦的附加脉冲锁模的 Nd:YLF 激光器 ..... 1179

多阶强度非线性条件下的光束传输研究 ..... 1184

傍轴光束薄透镜传输的统计行为 ..... 1191

Laser diode array side-pumped acousto-optic induced unidirectional operation

    Q-switched Nd:YAG slab ring laser ..... 1196

SG-II laser elementary research and precision SG-II Z program ..... 1299

SG-II solid-state laser ICF system ..... 1205

光束传输的 Schrödinger 形式理论研究 ..... 1211

A schrödinger formulation research for light beam propagation ..... 1220

ICF 固体激光驱动器前级系统中的脉冲整形 ..... 1231

混合单元柱面透镜列阵特性及优化 ..... 1245

利用模拟退火法实现不等宽单元柱面透镜列阵(CLA)的理论设计 ..... 1250

高功率激光系统光束传输的基本算法和程序编码 ..... 1255

利用模拟退火法实现不等宽单元柱面透镜列阵(CLA)的理论设计 ..... 1265

Fundamental algorithm and computational codes for the light beam propagation

    in high power laser system ..... 1270

## EVIDENCE, FROM SPACE RESOLVED SPECTRA, OF $2\omega_0$ HARMONIC GENERATION IN LASER IRRADIATED PLASMA FILAMENTS

Min GU, Weihan TAN, Zunqi LIN, Wenhua CHEN, Yuxia ZHENG, Wenyan YU and Ximing DENG  
*Shanghai Institute of Optics and Fine Mechanics, Academia Sinica, Shanghai, P.R. China*

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Space resolved spectra with both high spectral resolution ( $\sim 0.2 \text{ \AA}$ ) and spatial resolution ( $\sim 2 \text{ \mu m}$ ) of the second harmonic emission scattered at  $90^\circ$  to the laser axis were observed when both narrow band and broad band laser beams were used in an Al planar target experiment. Analysing many experimental phenomena, we have proved that the second harmonic emission observed at  $90^\circ$  to the laser axis is initiated by laser-plasma-filament interaction and not by planar-wave-plasma interaction. The experiments are, on the whole, in agreement with our theory.

### 1. Introduction

Two generation mechanics, namely linear conversion and parametric decay, for the second harmonic emission from laser plasma have been studied both experimentally and theoretically [1-13]. In terms of the resonance absorption theory based on the assumption that an obliquely incident planar wave with P polarization travels into a plasma with a linear gradient [1,2,14], it has been shown that the second harmonic emission resulting from the linear conversion is mainly emitted in the mirror-reflected direction of the incident laser. In the normally incident case, the linear conversion of the  $2\omega_0$  harmonic emission is very weak because the resonance absorption almost disappears. But, it has been found in ref. [15] that, when a laser beam is normally incident, two-dimensional microphotographs of the second harmonic emission scattered at  $90^\circ$  to the laser axis display many filamentary structures with a length of  $125 \text{ \mu m}$ , the transverse scale of which is about  $5\text{--}15 \text{ \mu m}$ . Unfortunately, no satisfactory physical explanation for this phenomena has been put forward. On the other hand, the time resolved spectra, as well as time and space resolved structures, of the second harmonic emission have been observed at  $90^\circ$  to the laser axis in our experiment [12,13]. The filamentary structures extend to  $180 \text{ \mu m}$  along the incident direction, close to the length of filaments [16]. All

these phenomena can not be explained by the planar wave interaction theory. Therefore, we have considered [14] a new mechanism for the second harmonic emission from plasma filaments, which shows that when a laser beam interacts with plasma filaments, the  $2\omega_0$  harmonic emission caused by the linear conversion is mainly emitted in a direction perpendicular to the laser axis.

In this paper, we present a simple description of the mechanism for the second harmonic emission from plasma filaments [14]. Then, both broad band and narrow band laser beams are used in the prepulse and non-prepulse irradiance, irradiating on an Al planar target normally. The second harmonic space resolved spectra scattered at  $90^\circ$  to the laser axis were thus observed. From these spectra, it has been found that the second harmonic emission with a luminescent length of  $180 \text{ \mu m}$  extends outward from the critical surface. In this luminescent region, there exist no spectral shifts. Only in the prepulse case, do some red and blue shifted peaks emerge near the critical surface. By comparing the experimental results in the broad band and narrow band irradiance, the new mechanism for the second harmonic emission from a plasma filament [14] may be proved. The experiments are in general, consistent with the theory.

## 2. The mechanism for the $2\omega_0$ harmonic emission in filaments

In ref. [14], the influence of laser plasma filaments on the linear conversion of the  $2\omega_0$  harmonic emission were studied in detail. Considering a filament with both a linear density gradient along the  $z$ -direction and a radial density distribution, and assuming that a laser beam travels along the  $z$ -direction, one can find that there exists an intense local field of the fundamental wave near the radial resonance point  $r_0$  (when  $r=r_0$ , the dielectric coefficient is equal to zero), which is called the radial tunnel effect [14]. Thus the characteristics of the second harmonic emission generated by this effect are the following.

(i) If the fundamental wave is symmetric about the  $z$ -axis, the intensity of the second harmonic emission is zero in the  $z$ -direction, but intense in the direction perpendicular to the incident laser.

(ii) If the fundamental wave is asymmetric about the  $z$ -axis, the second harmonic generation is emitted both in the  $z$ -direction and in the direction perpendicular to the incident laser. Generally, the intensity in the former case is smaller than that in the latter case and depends on the symmetry of the fundamental wave about the  $z$ -axis. The better the symmetry, the smaller the intensity in the  $z$ -direction.

(iii) The second emission displays a large luminescent region, extending outward from the critical surface along the  $z$ -axis. The luminescent length is of the same order as that of a plasma filament.

(iv) Since the second harmonic emission is caused by the linear conversion, its spectrum shows no red shifts.

## 3. Experimental setup and results

### 3.1. Experimental setup

The experiments were carried out at the Six Laser Beam Facility in the Shanghai Institute of Optics and Fine Mechanics. It has been shown in our previous experiments [17] that the laser illumination on the target surface in narrow band irradiance is non-uniform and filaments are easily produced. Conversely, in the broad band irradiance the laser illumination

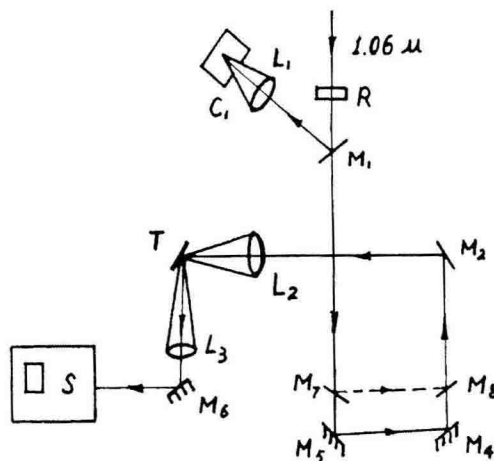


Fig. 1. Experimental setup.

is uniform and it is difficult to initiate the filamentation process. Therefore, the influences of the plasma filament on the second harmonic emission can be studied by adopting the broad band and narrow band lasers. The methods used to generate broad band and narrow band lasers have been described in refs. [17,18]. The broad band laser had a bandwidth of  $\sim 30 \text{ \AA}$  while the narrow band laser bandwidth was  $0.2 \text{ \AA}$ . Both broad band and narrow band lasers had an output energy of  $0.4\text{--}10 \text{ J}$ , pulse width  $250 \text{ ps}$ , and power density  $(0.3\text{--}8) \times 10^{14} \text{ W/cm}^2$ .

The experimental arrangement is shown in fig. 1, where  $M_1$ ,  $C_1$  and  $L_1$  are sampling mirror, energy calorimeter and focusing lens, respectively, for the measurement of the incident laser energy. Both broad and narrow band incident lasers then passed through a quartz optical rotation plate  $R$  with  $45^\circ$  left- or  $45^\circ$  right-handed rotation, becoming  $P$  (horizontally) or  $S$  (vertically) polarized with respect to the target plane. Two partly reflecting plates  $M_7$  and  $M_8$  for the wavelength of  $1.06 \mu\text{m}$  were inserted in the path to form a prepulse with a magnitude of  $0.1\%$  of the main pulse energy and an arrival time ahead of the main pulse  $0.15 \text{ ns}$ . The incident laser was focused by an  $f/2$  aspherical lens  $L_2$  on an Al planar target surface with an incident angle  $\theta = 3^\circ$ , resulting in the second harmonic emission.

The spectrograph  $S$ , with a dispersive power of  $16 \text{ \AA/mm}$  for the wavelength of  $0.53 \mu\text{m}$ , was oriented at  $90^\circ$  to the incident laser, and its slit, the length and width of which are  $6 \text{ mm} \times 100 \mu\text{m}$ , was placed



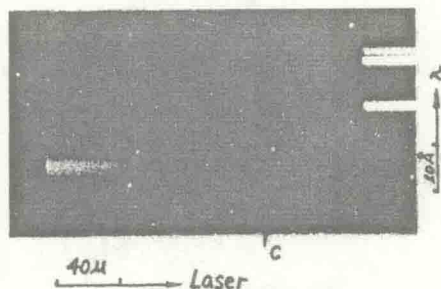


Fig. 2.  $2\omega_0$  harmonic space resolved spectrum of irradiation no. 17 with narrow band laser irradiance on an Al planar target and incident angle of  $3^\circ$ , energy 3.0 J,  $45^\circ$  polarization.

in the horizontal direction. By using micro-objective  $L_3$  ( $f=100\ \mu\text{m}$ ) and mirror  $M_6$  for the wavelength of  $0.53\ \mu\text{m}$ , a sampling window at the target normal,  $5\ \mu\text{m} \times 280\ \mu\text{m}$ , was formed. Thus, we can obtain the second harmonic space resolved spectra produced by plasma filaments with both high spatial resolution ( $\sim 2\ \mu\text{m}$ ) and spectral resolution ( $\sim 0.2\ \text{\AA}$ ). Some interference filters with central wavelength  $0.53\ \mu\text{m}$  and totally reflecting plates for  $1.06\ \mu\text{m}$  were set in front of the spectrograph slit, so that one could adjust the signal intensity and cut out the scattered lights.

### 3.2. Experimental results

The second harmonic space resolved spectra observed at  $90^\circ$  to the incident laser under the condition of non-prepulse and prepulse irradiance are shown in figs. 2, 3 and 4, respectively, calibrated by spectral lines of Ne atoms. The wavelength of the first Ne spectral line near the  $2\omega_0$  harmonic spectra is  $5330.78\ \text{\AA}$ . Analyzing these spectra in detail, one could notice the following features.

#### 3.2.1. Non-prepulse case

(i) The  $2\omega_0$  harmonic luminescent length along the incident laser varies with the incident energy. When the incident energy is smaller (about 3 J), the  $2\omega_0$  harmonic emission extends outward from a position,  $60\ \mu\text{m}$  from the critical surface (see fig. 2, where point c denotes the position of the critical surface). The luminescent length in the detecting range of the spectrograph is about  $30\text{--}40\ \mu\text{m}$ . If the energy increases further, for example, the incident energy is

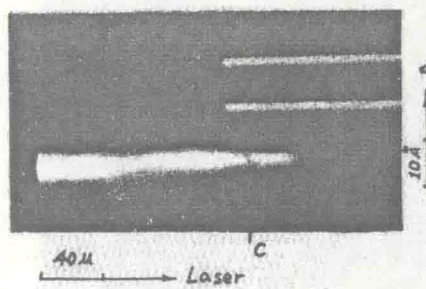


Fig. 3.  $2\omega_0$  harmonic space resolved spectrum of irradiation no. 21 with narrow band laser irradiance on an Al planar target and incident angle of  $3^\circ$ , energy 6.5 J, vertical polarization.

7 J, the  $2\omega_0$  harmonic luminescent length then becomes  $180\ \mu\text{m}$ , extending to the critical surface.

(ii) The central position of the  $2\omega_0$  harmonic space resolved spectrum shows no red shifts within the whole luminescent region. The spectral width is about  $5.6\ \text{\AA}$  near the critical surface and  $7.2\ \text{\AA}$  far away from the critical surface.

(iii) In the case of narrow band irradiance, the second harmonic emission was generated not only in the backscattering direction but also in the direction perpendicular to the incident laser even if the incident energy is smaller. However, when a broad band laser irradiates an Al planar target, the second harmonic intensity in the direction perpendicular to the incident laser is too small to be recorded by the spectrograph.

#### 3.2.2. Prepulse case

Some interesting results obtained in the prepulse irradiance are displayed in fig. 4. When a narrow band laser with a prepulse irradiates an Al planar target, the intense second harmonic emission with a luminescent length of  $120\ \mu\text{m}$  along the incident laser is still observed in the direction perpendicular to the incident laser. Besides, the central position of the spectrum with a width of  $4.8\ \text{\AA}$  shows no red shifts. Conversely, in the broad band case, only when the incident energy is larger than 10 J (corresponding to a power density of  $8 \times 10^{14}\ \text{W}/\text{cm}^2$ ), can the second harmonic emission be detected in the direction perpendicular to the incident laser. Comparing figs. 2 and 3 with fig. 4, one can find the following differences near the critical surface.

(i) The  $2\omega_0$  harmonic emission is more intense

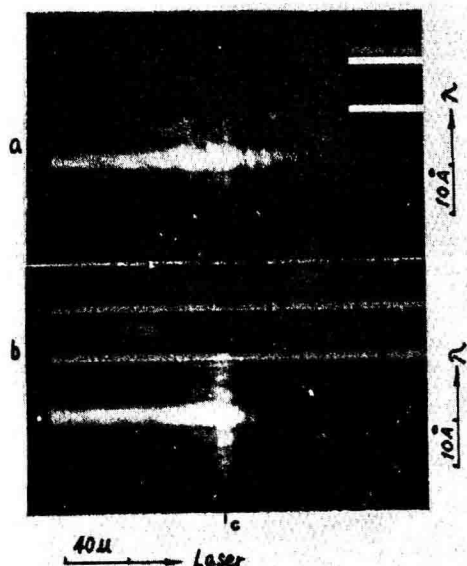


Fig. 4.  $2\omega_0$  harmonic space resolved spectra with narrow band laser irradiance on an Al planar target and incident angle of  $3^\circ$ . (a) Irradiation no. 89, 2.9 J,  $45^\circ$  polarization. (b) Irradiation no. 90, 2.5 J,  $45^\circ$  polarization.

near the critical surface than that in the other region.

(ii) There are some fine space fringes with intervals of  $8 \mu\text{m}$  along the incident laser (see fig. 4a).

(iii) From fig. 4, as well as its densitometric traces in fig. 5, it is shown that there are some symmetric red and blue shifted peaks. The interval between peaks is about  $3.8 \text{ \AA}$ .

#### 4. Discussion

The second harmonic space resolved spectra observed above in the lateral direction show a lumi-

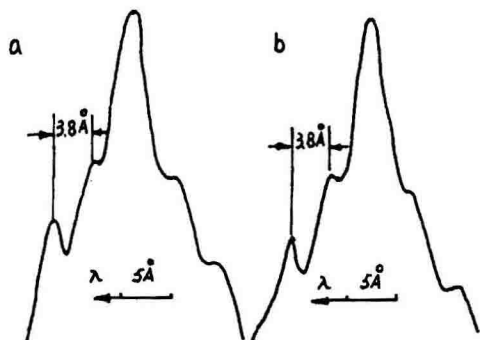


Fig. 5.  $2\omega_0$  harmonic space resolved spectrum densitometric traces corresponding to fig. 4.

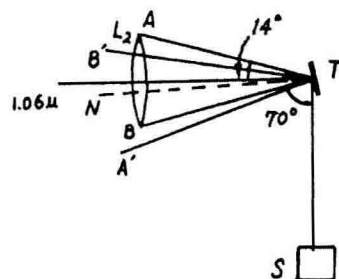


Fig. 6. Shooting diagram.

nescent length of  $180 \mu\text{m}$  along the incident laser, which is consistent with the length ( $\sim 180 \mu\text{m}$ ) observed in the  $2\omega_0$  harmonic time and space resolved structures in the same direction [13]. It is difficult to explain why the  $2\omega_0$  harmonic emission displays such a large scale out of the critical surface according to the linear conversion theory based on the planar wave-plasma interaction [1,2,14]. First, the  $2\omega_0$  harmonic emission could only be generated in the mirror-reflected direction of the incident laser [14], and its intensity is very weak in the normal incident case because the resonance absorption almost disappears [17]. In fact the incident angle is about  $3^\circ$  and the convergence angle of lens  $L_4$  with respect to the target surface is  $14^\circ$  (see fig. 6) in our experiments. Therefore, the ray passing by the point A is reflected by the target surface, then forms an angle of  $70^\circ$  with respect to the direction perpendicular the incident laser. Thus, the intensity of the  $2\omega_0$  harmonic emission in the lateral direction should be zero. Second, the  $2\omega_0$  harmonic emission can only be generated near the critical surface and could not appear in a range of  $180 \mu\text{m}$  out of the critical surface according to the planar wave-plasma interaction theory [1,2]. Finally, if the  $2\omega_0$  harmonic emission resulted from the parametric decay [4] its spectrum should show a large red shift out of the critical surface, for example, the red shift of Al targets is in a range of  $10\text{--}20 \text{ \AA}$ . But, the  $2\omega_0$  harmonic space resolved spectra display, in our experiments, no red shifts within the whole luminescent region.

On the basis of the above discussion, it may be conceivable that the second harmonic emission observed in the lateral direction arises from the interaction of the laser beam with plasma filaments rather than the interaction of the planar wave with a plasma. In accordance with theory summarized in sect. 2, all

the above features can be explained. Because the narrow band laser irradiance on the target surface is non-uniform and it is easy to obtain plasma filaments, in which the fundamental wave has an asymmetric distribution about the filamentary axis; while the uniform illumination in the broad band irradiances makes the filamentation process difficult to generate, the  $2\omega_0$  harmonic emission in the lateral direction is intense in the narrow band case and too weak to be observed in the broad band case.

It has been known that the laser irradiated plasma filaments extend outward from the critical surface [16], and there exists an intense radial field (the radial tunnel effect) at each point along the filamentary axis, which leads to the  $2\omega_0$  harmonic generation. Therefore, the  $2\omega_0$  harmonic luminescent region extends outward from the critical surface, the length of which is about equal to that of a plasma filament. On the other hand, it is the linear conversion of the  $2\omega_0$  harmonic generation that we discuss in this paper. Furthermore, the spectrograph slit placed in the horizontal direction coincides with the filamentary axis so that a filament can be imaged on the slit. Therefore, the  $2\omega_0$  harmonic space resolved spectrum could demonstrate a spectral line with a certain width and length (equal to the length of filaments), showing no spectral shifts.

Now, we begin to make further analyses of the interesting phenomena in the prepulse irradiance. Since a prepulse generates a large scale plasma corresponding to a lower density, a large part of the incident laser can arrive at the critical surface, causing the resonance absorption initiated by self-focusing filamentation described in ref. [17]. On the other hand, a radial tunnel effect also emerges, resulting in an intense local field at the radial resonance point [14]. These two effects all generate the linear conversion of the  $2\omega_0$  harmonic emission so as to form an intense  $2\omega_0$  harmonic region near the critical surface. However, the former effect will disappear out of the critical surface so that the  $2\omega_0$  harmonic intensity becomes weak.

The emergence of the red and blue shifted peaks near the critical surface (fig. 4) arises from the wave vector limitation of the Langmuir wave in a modulated plasma [12]. Referring to ref. [12], one can express the wavelength difference between shifted peaks as

$$\Delta\lambda_2 = (4\lambda_2/\omega_2)\bar{k}(ZT_e/m_i)^{1/2}. \quad (1)$$

For the prepulse case, some nonlinear processes, such as two plasma decay and Raman scattering are produced in a larger scale filament. Thus the electron temperature rises, owing to the generation of a lot of superhot electrons in the nonlinear processes. When  $T_e = 4$  keV [19], then  $\Delta\lambda_2 = 3.6$  Å, close to the value of 3.8 Å measured in the experiments. Another important result caused by the plasma modulation is that the second harmonic space fringes can emerge near the critical surface [13]. If a prepulse generates an expanding plasma with a velocity of 0.42 cm/ns [20], the plasma characteristic length  $z_0$  is  $0.42 \times 1.5 = 6.3$  cm. Therefore, the fringe interval becomes 8.1 µm, calculated by the following formula

$$\Delta x = 1.5[z_0(\lambda_0/2\pi)^2]^{1/3}, \quad (2)$$

in agreement with that in the experiments. However, the fringe interval was calculated as  $\Delta x = 4.4$  µm in the non-prepulse case [13]. These fringes bent either in or out with the time evolution [13]. As the space resolved spectra are integrated with respect to the time, one can not observe the clear space fringes in figs. 2 and 3.

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## THE MECHANISM FOR THE SECOND HARMONIC GENERATION IN LASER IRRADIATED MICROTUBE TARGETS

Wenhua CHEN, Min GU, Zunqi LIN, Wenyan YU, Weiha TAN and Ximing DENG

*Shanghai Institute of Optics and Fine Mechanics, Academia Sinica, Shanghai, P.R. China*

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Reported in this paper are the  $2\omega_0$  harmonic space and time resolved structures, observed at the back-scattering direction in laser irradiated microtube target experiments. The process of laser-microtube interaction has been analysed. According to the plasma filament interaction theory, primarily the special phenomena are explained of the back-scattering  $2\omega_0$  harmonic emission within the microtube.

### 1. Introduction

Recently, a high population inversion between the  $1s3p$  level and  $1s4p$  level of He-like  $Mg^{+10}$  has been obtained, using a high power laser to irradiate microtube targets in the soft X-ray wavelength band [1].

Since the interaction of a laser with the microtube targets is rather sophisticated, it is necessary to use different diagnostic methods in our experiments. Presented here are the time and space resolved structures of the second harmonic emission observed in the back-scattering direction. By using the streak camera techniques, some interesting phenomena have been achieved. Analyzing these results, we can get a better understanding of the mechanism of the high population inversion.

### 2. Experiment arrangement

The experiments were carried out at the Six Beam Laser Facility in the Shanghai Institute of Optics and Fine Mechanics, Academia Sinica. The FWHM of the laser pulse with a spectral width of  $0.2 \text{ \AA}$  was in the range of 100–250 ps. The output energy was 1–10 J, and the power density  $5 \times 10^{13}$ – $3 \times 10^{14} \text{ W/cm}^2$ . The laser beam was focused by an aspherical lens  $L_1$  with a focusing spot of 60–80  $\mu\text{m}$  (see fig. 1) on the microtube target surface.

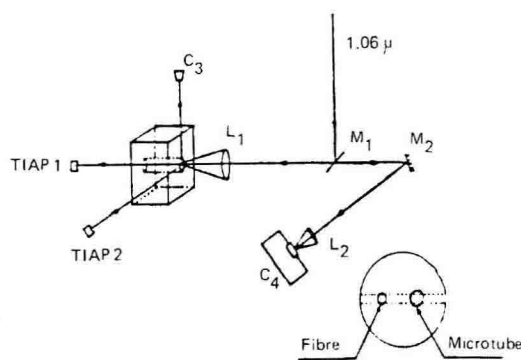


Fig. 1. The experimental setup.

Along and perpendicular to the microtube axis, two TLAP crystal spectrographs  $C_1$ ,  $C_2$ , the main parameters of which were presented in ref. [2], were set. Thus, we can get resonant emission of the Mg ions inside and outside the microtube. Besides, there was a pinhole camera above the microtube.

The second harmonic emission of the plasma passing through an imaging system formed by lens  $L_1$  and a mirror  $M_2$  with wavelength of  $0.53 \mu\text{m}$  was focused on the streak camera slit, which was adjusted to coincide with the diameter of the microtube.

In order to determine the mechanisms for the second harmonic emission, it is necessary to obtain the incident laser pulse profile. For this purpose, the laser pulse signal from the amplifier of the laser system was conducted to one end of the streak camera's slit,