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超快涡旋光场驱动空气激射产生与调控

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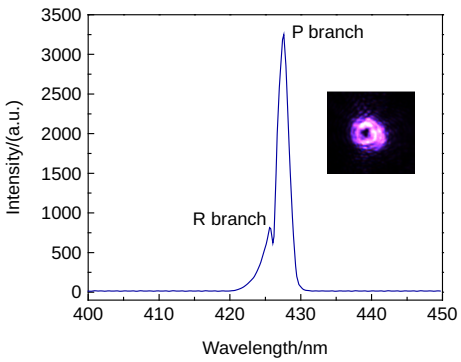

摘要：本文阐述了通过单束近红外泵浦光构造的调制光场产生和调控涡旋氮离子空气激射，经检测泵浦光和信号光的轨道角动量量子数，发现了空气激射中轨道角动量转移和守恒现象，揭示了自种子光诱导产生涡旋氮离子空气激射的物理机制。通过改变泵浦涡旋光脉冲能量，实验发现在输入光脉冲能量较高时，涡旋氮离子激射产率相较于传统高斯型氮离子激射产率更高，分别选取低能量和高能量泵浦光条件改变实验气体压强，得到空气激射产率对压强的不同依赖关系。相关结论丰富了涡旋光场调控空气激射的研究成果，扩展了涡旋光场驱动产生的空气激射在远程雷达探测等领域的应用前景。

关键词：涡旋光场；空气激射；自种子

The English title and abstract appear at the end of the paper.

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1　引　言

光的横向结构在较长时间内并没有受到人们的广泛关注，伴随着光学技术不断攀升和各类调控器件的飞速发展，涡旋光被发现和构建。这种新型光场不仅在空间中呈螺旋形扭曲状，同时具有相位或偏振奇点特性。不同于寻常简单的沿直线传播光场，波粒二象性使得螺旋绕轴行进的光子具有了轨道角动量，光子角动量即被分解成为轨道角动量 (orbital angular momentum, OAM) 和自旋角动量 (spin angular momentum, SAM)。其中，OAM 与光场波前属性有关，受横截面复电场分布影响，SAM 表征的是光场偏振属性，可在圆偏光的电、磁场旋转综合作用下形成。为了便于表征涡旋光轨道角动量的大小，通常用拓扑荷数 l 来描述单位波长下涡旋扭曲数量，l 越大，光场空间旋转速度越快。随着 l 的增加，相位进行 2π 整数倍调整，强度相位综合抵消结果下光场中心暗区逐渐增大。涡旋光场的这一时变旋转特性为结构光调控提供了全新维度的自由度[1-4]，在光操纵粒子[5-6]、光信息存储[7]、量子纠缠[8] 等学术领域催生出许多新研究分支。

空气激射对远程探测[9-14] 领域有着极其重要的应用前景，用于雷达探测的散射信号主要为非相干成分，其强度随距离平方衰减，对雷达探测的信噪比和灵敏度产生严重影响，而空气激射具有很高的相干性和准直度，其远程无腔光放大的特性恰好满足了远程探测的发展需要。研究人员针对空气激射特别是其主要成分离化后产生的 N_2^+ 激射开展了大量研究，主要研究热点在于 N_2^+ 空气激射的产生机制以及如何进行调控放大[15-21]，前者主

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要关注多电子态耦合跃迁[15-16]、电子碰撞再激发[17-19]、分子转动瞬态增益[20]等机制在N_2^+空气激射产生中的贡献，后者探索通过调控泵浦光波长[17]以及构造偏振旋转光场[21]等方式以提高空气激射的产率。然而受限于光强的钳制效应，空气激射的强度相对较低且调控范围有限。除了对振幅、频率、相位、偏振等参数进行操控，将超快激光与涡旋光场结合，可从三维光场层面拓宽到时空维度，在时-频域拓宽对空气激射的精密调控效果，为远程生成、放大和灵活操控涡旋空气激射开辟了新途径[22-27]。近年来 Hu 等[22]与 Gao 等[23]在 391 nm 激射实验中验证了 OAM 信息从驱动泵浦光场传递给增益介质N_2^+的过程。Shen 等[24]通过将拓扑荷数高达 10 阶的涡旋种子注入飞秒激光成丝产生的等离子体通道，获得了拓扑荷数可调谐 (l 从 1 至 10) 的高增益涡旋空气激射。由于 428 nm 激射相较于 391 nm 激射在电离后N_2^+的$X^2\Sigma_g^+$ (v = 1) 态粒子布居数存在显著差异[21]，可带来不同的增益行为和调控变化规律，为进一步研究空气激射产生机理过程，探索新涡旋光场下空气激射的调控效果，本文围绕 428 nm 特殊谱线的N_2^+空气激射展开研究，通过分析前向光谱及背后的产生机理过程，探索生成的N_2^+涡旋空气激射在光强、气压等不同条件下的产率变化规律，以丰富涡旋空气激射调控的研究成果，推动其在远程雷达探测等领域的应用。

2 超快涡旋光场驱动空气激射产生与检测装置

由于产生的涡旋光携带的拓扑荷数相对固定，采用实验中简单快捷、效率较高的螺旋相位板法[28]产生涡旋光。空气激射产生和观测实验装置如图 1 所示，研究中采用泵浦光源为钛宝石激光系统 (Ti: sapphire, Coherent Astrella)，输出的中心波长为 800 nm，脉宽为 35 fs，最大脉冲能量为 7 mJ，重复频率为 1 kHz 的 800 nm 近红外激光，从钛宝石激光器输出的泵浦光通过螺旋相位板 (spiral phase plate, SPP) 形成涡旋泵浦光，随后经过一个焦距 f = 20 cm 的透镜 (记为 F1)，在空气的主要成分氮气腔室中进一步聚焦，形成约 10 mm 的等离子体光丝，同时在前向生成N_2^+激射。如图 1(a) 所示，从N_2中出射的光信号经过一个焦距为 f = 15 cm 的透镜 (记为 F2) 准直，通过短波通滤波片 (430 nm Filter) 过滤掉剩余的 800 nm 波段泵浦光和部分超连续背景光，最终的信号光经光纤导入到光谱仪 (HR2000+ Spectrometer, Ocean Optics) 中进行数据采集。实验中一般可直接观测到涡旋光圆环形的强度分布，并不能直接检测出涡旋光的螺旋相位结构，从而判断涡旋光的拓扑荷数，因柱透镜法在实验设备上只需要柱透镜这一个光学元件和一个 CCD 相机即可直接测量涡旋光的拓扑荷数，并且测量结果清晰，实验中采取了柱透镜法测量涡旋光的拓扑荷数 l [29]。拓扑荷数测量装置如图 1(b) 所示，出射光经上述准直过滤后通过柱透镜 (cylindrical lens, CL) 聚进 CCD 相机 (MER-050-560U3C) 中，涡旋光场经柱透镜后形成狭缝形的光强分布，狭缝数量对应拓扑荷数，由此可对信号光的拓扑荷数进行判定。

3 涡旋空气激射产生与调控实验结果分析

3.1 前向涡旋N_2^+激射光谱成分分析

如图 2 所示为实验中采集的通过单束泵浦光构造的调制光场产生的前向N_2^+空气激射光谱，其在 428 nm 附近形成了强窄线激射谱。根据跃迁选择定则，N_2^+激射主

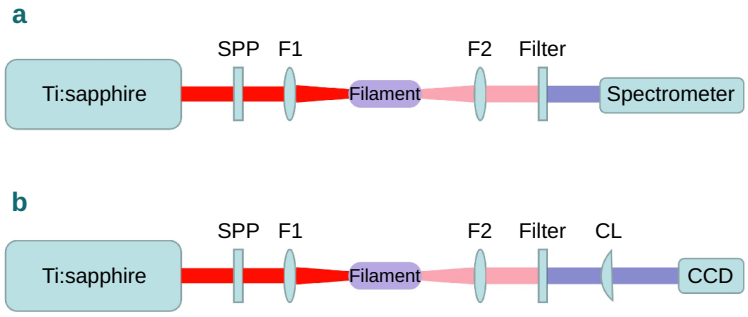

图 1 涡旋泵浦光驱动N_2^+空气激射产生实验装置图。(a) 谱线观测；(b) 拓扑荷数测量

Fig. 1 Schematic diagram of vortex N_2^+ air radiation generated by vortex pumping beam. (a) Observation by spectrometer; (b) Topological charge number measurement

要来自 N_2^+的第二激发态 $B^2\Sigma_u^+$到基态 $X^2\Sigma_g^+$之间的单光子辐射跃迁。$B^2\Sigma_u^+$态和 $X^2\Sigma_g^+$态不同振动能级上布居的粒子发生跃迁时对应不同波长的 N_2^+激射光谱，本文主要研究 N_2^+从 $B^2\Sigma_u^+$ (υ'= 0) 振动能级到 $X^2\Sigma_g^+$ (υ = 1) 振动能级跃迁的 N_2^+激射现象，其能量差对应的跃迁光子波长在 428 nm 附近。从图中可以清晰地发现，泵浦光作用下产生的 428 nm 激射劈裂为两个不同高低的峰。由于氮气分子经强激光电离后，形成的 N_2^+每个电子态上包含了多个转动能级结构，图中的双峰结构分别为 N_2^+里 $B^2\Sigma_u^+$ (υ' = 0) 能级到 $X^2\Sigma_g^+$ (υ = 1) 能级跃迁的 P 支和 R 支，此结果由 N_2^+转动跃迁导致[30]。

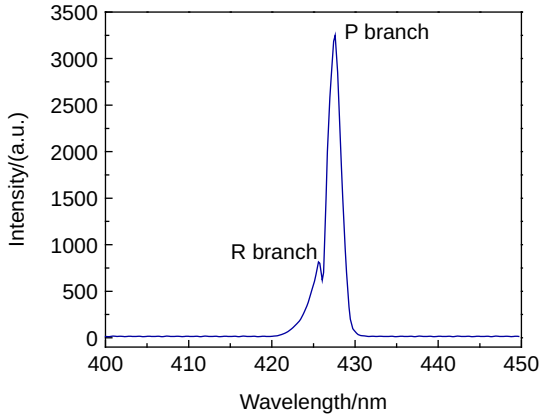

图 2 428 nm N_2^+空气激射光谱

Fig. 2 Spectrum of 428 nm N_2^+ lasing

3.2 涡旋 N_2^+激射的拓扑荷数和产生机制

实验中入射的泵浦激光存在一定谱宽，经螺旋相位板后，光场转化为携带了 OAM 模式的涡旋叠加泵浦光。实际上，在上述 N_2^+激射产生过程中，涡旋泵浦光中 800 nm 波段参与主要贡献，生成的 428 nm 激射的拓扑荷数 (即 OAM 量子数) 相对固定。而对于泵浦光，用平均拓扑荷数以表达其宽谱涡旋拓扑荷数的综合叠加效果。为了检测形成的 428 nm N_2^+空气激射在本实验中的拓扑荷数，在输入脉冲能量约为3 mJ 时，通过 CCD 观测 0.01 MPa 气压下 N_2^+空气激射的远场光斑和经柱透镜后的光斑，如图 3(a, b) 所示。同时，为了对比入射涡旋泵浦光情况，在未注入氮气下将直接生成的涡旋泵浦光及经柱透镜后的光斑结果呈现在图 3(c, d) 中。

从图 3(a) 中可以发现，实验中产生的 428 nm N_2^+激射远场光斑的光强分布与空间涡旋光场一致，为中心有空洞的圆环形。图 3(b) 为信号光经过柱透镜后狭缝式的

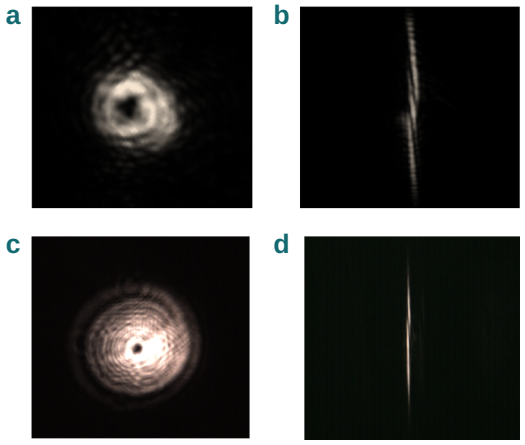

图 3 N_2^+激射与泵浦光光斑对照实验结果。(a) 428 nm N_2^+激射的远场光斑和 (b) 经过柱透镜后的光斑；(c) 涡旋泵浦光光斑和 (d) 经过柱透镜后的光斑

Fig. 3 The experimental spots of N_2^+ lasing compared with the spots of the pumping laser. (a) The far-field spot of N_2^+ lasing and (b) the spot after passing through cylindrical lens; (c) The spot of vortex pumping laser and (d) the spot after passing through cylindrical lens

光强分布，说明了产生的 428 nm N_2^+激射的涡旋结构光性质。由于狭缝数量为 2，据此分析，在涡旋泵浦光场作用下产生的 428 nm N_2^+涡旋激射的拓扑荷数为 2 (l = 2)。通过对比图 3(c) 和图 3(d)，泵浦光场经柱透镜后的狭缝数为 1，经检验的涡旋泵浦光的平均拓扑荷数为 1 (l = 1)。在螺旋相位板的作用下 800 nm 泵浦光首先转化为中心波段平均拓扑荷数为 1 (l = 1) 的涡旋光场，其主要成分作用于氮气分子，一方面由于基频光携带有 OAM，氮气分子通过光致电离过程吸收携带轨道角动量的 800 nm 光子平行跃迁到 N_2^+的 $B^2\Sigma_u^+$态，其角动量储存在该电子态的振动能级中，另一方面单电离后的 N_2^+通过吸收 800 nm 的单光子，从 $X^2\Sigma_g^+$基态垂直跃迁到 $A^2\Pi_u$ 态激发态，间接增强了 $B^2\Sigma_u^+$态和 $X^2\Sigma_g^+$态间的粒子布居数反转效应。实验中信号光拓扑荷数为原泵浦光平均拓扑荷数的两倍，这归结于 N_2^+激射的自种子光放大的产生机制。涡旋泵浦光在不均匀的等离子体通道内产生二倍频信号，800 nm 泵浦激光的二倍频信号波段接近 N_2^+的 $B^2\Sigma_u^+$态到 $X^2\Sigma_g^+$态的跃迁波长，可以作为种子光有效诱导产生 N_2^+激射。在此过程中，由于基频光携带有 OAM，根据角动量守恒，两个携带能量的 800 nm 光子转化为一个携带有能量的 400 nm 光子，根据受激辐射理论，由 $B^2\Sigma_u^+$态到 $X^2\Sigma_g^+$态跃迁产生的光子应和诱导的光子具有相同的相位，即轨道角动量属性不变，由此，在涡旋泵浦光驱动下产生了拓扑荷数为 2 的涡旋 N_2^+空气激

射，与观测到的 428 nm N_2^+空气激射拓扑荷数检测结果相符。

从上述实验结果可以看出，超快涡旋光场驱动空气激射的产生是泵浦光空间拓扑结构深度耦合参与电离、种子形成和受激放大全过程的综合结果。首先，428 nm 信号同时具有转动精细结构和稳定的涡旋空间模式，说明其产生来自于与 N_2^+能级跃迁密切相关的相干辐射。信号光的拓扑荷数相较于基频泵浦光出现倍增，支持了自种子机制下从基频涡旋光和二倍频种子再到受激辐射输出这一过程，在 $B^2\Sigma_u^+$态到 $X^2\Sigma_g^+$态跃迁放大中保留了种子场的螺旋相位。由此生成的空气激射拓展到远程领域，可对空间不同角度进行雷达探测，相较于传统雷达探测手段具有更大的潜在应用空间。

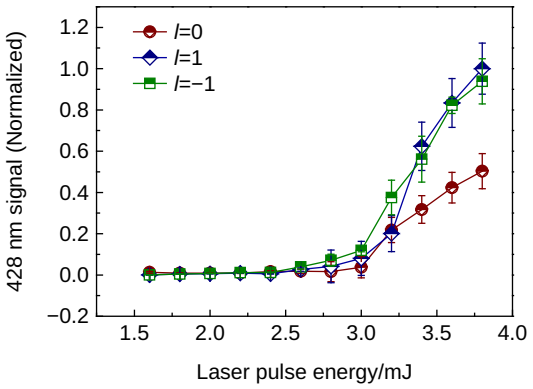

图 4 l 分别为 0，1，−1 三种情况下 428 nm N_2^+激射产率随泵浦光脉冲能量的变化

Fig. 4 428 nm N_2^+ lasing yield as a function of pump pulse energy with l = 0, 1, −1

3.3 涡旋 N_2^+激射的产率调控

为进一步探索和理解涡旋光场下 N_2^+空气激射的产率调控规律，首先通过改变泵浦光脉冲能量，在相同条件下和高斯型 N_2^+激射的产率调控结果进行比较，研究涡旋 N_2^+激射产率随泵浦光脉冲能量的变化规律。图 4 表示在 0.01 MPa 气压条件下 428 nm N_2^+激射产率随泵浦光脉冲能量的变化。可以看出，随着泵浦激光能量从 1.6 mJ 增加到 3.8 mJ，在较低泵浦光脉冲能量 (本实验条件中 3 mJ 以内) 区域中，无论是 $l = 1$ 还是 $l = -1$，由涡旋光场诱导产生的 428 nm N_2^+激射产率和高斯光场下生成的 428 nm N_2^+激射产率相差不大；当泵浦光脉冲能量较高时，特别是在 3.4 mJ 以上，$l = 1$ 和$l = -1$ 下涡旋 N_2^+激射的产率相较于传统高斯型 N_2^+激射的产率有着较为明显的升高，且形成互为验证的关系。由此可见，涡旋泵浦光特殊的圆环形光强分布十分有利于 N_2^+激射的调控，经聚焦后形成的等离子体中光强钳制效应的阈值被提高[31]，此时在光丝处的光强能够更好地促进 N_2^+的粒子数反转，带来更高的产率。在更高泵浦能量输入情况下涡旋 N_2^+激射产率的显著提高，有望将结构光驱动的空气激射推动到远程探测领域，尽管远程激发和调控空气激射是一个极具吸引力的挑战，利用空间结构光场的特殊优势有助于进一步探索和实现空气激射的远程控制。

为探究低能量泵浦和高能量泵浦下 N_2^+激射产率的变化，分别针对低输入激光能量和高输入激光能量两种情形改变气体压强，得到如图 5 所示的实验结果。其中，在 1.8 mJ 的低输入激光能量下，如图 5(a) 所示，高斯光得到的 428 nm N_2^+激射产率整体较高，在 0.01 MPa 下达到了峰值，随后逐渐下降；当输入激光能量提升到 3.4 mJ 时，如图 5(b) 所示，由于涡旋光场形成的聚焦光丝降低了等离子体密度，导致钳制光强的增加，涡旋光相较于传统高斯光的调控优势得以体现，拓扑荷数为−1 和 1 下涡旋光场驱动产生的 N_2^+激射产率均有着较为明显的提升，此外，涡旋光对应的饱和气压相对于高斯光的饱和气压增加了接近 0.01 MPa。在低能区下，对于高斯能量相对集中的中间区域，涡旋模式下转变为强度为 0 的奇点，导致激光能量的分散，涡旋光横截面内的峰值强度明显低于高斯光场，峰值光强的不足，粒子数反转建立受限，得到的 428 nm N_2^+激射产率随气压变化整体偏低，而高斯光场下仍可获得一定能量的激射输出；对于高能区，涡旋光场的能量分布相对更为均匀，涡旋光更高的钳制阈值、较低等离子体密度以及更高饱和气压共同扩展了有效增益窗口，使其在空气激射增强和参量调控方面表现出更明显的优势，且在高泵浦激光能量下，自种子放大效应在 428 nm N_2^+激射产生和建立过程中贡献更为明显，最终带来优于传统高斯光场的空气激射产率调控的结果。

综上，轨道角动量不仅可以作为空气激射输出的表征自由度，还可为调控增益建立、非线性频率转换和远程相干辐射方向性等提供有效手段。涡旋光场对 N_2^+空气激射的特殊调控效果，使得携带轨道角动量的空气激射对目标旋转方向的探测成为可能，同时可辅助实现复杂手性分子的拉曼光谱分析。相关研究结果表明，随着涡旋光场拓扑荷数以及能量的增加，光束自聚焦强度会降低，可能打破克尔自聚焦与等离子体发散之间的平衡[32]，这为涡旋光场驱动的空气激射远程探测应用提供

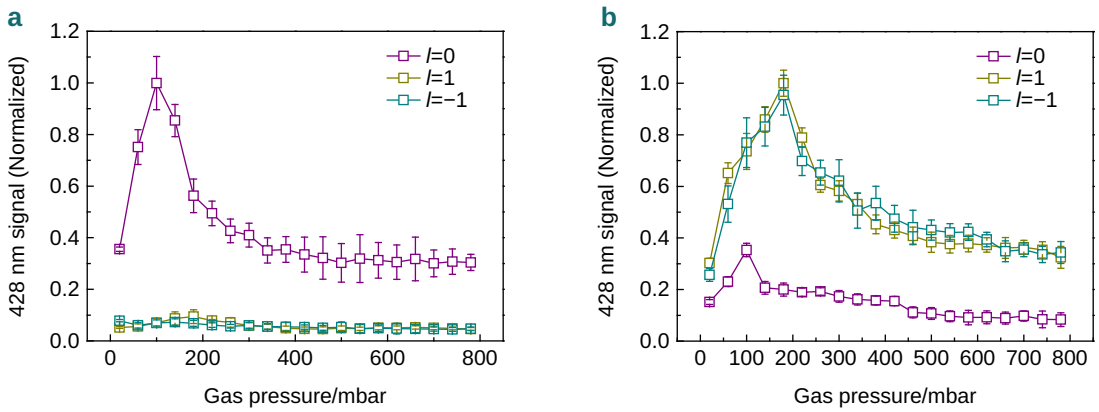

图 5 不同泵浦能量下N_2^+激射产率随气压的变化规律。*l* 分别为 0，1，−1 三种情况下 (a) 低泵浦能量和 (b) 高泵浦能量条件下 428 nm N_2^+激射产率随气压的变化

Fig. 5 N_2^+ radiation yield as a function of pressure under different pump pulse energies. 428 nm N_2^+ radiation yield as a function of pressure with *l* = 0, 1, −1 under the (a) low and (b) high pump pulse energy

了更多可能性。

4 结 论

本文针对传统高斯光场下空气激射调控强度受限以及尚不明确的产生机制等问题，通过构建涡旋光场产生涡旋空气激射，在高光强条件下实现了超越传统高斯空气激射的高强度涡旋空气激射，通过分析产生的前向 428 nm 双支光谱成分，阐释 N_2^+空气激射的产生机理过程，并研究其在光强、气压等不同条件下的产率变化规律，进一步丰富了空气激射产生机制研究成果。传统激光与涡旋光场的结合下，空气激射的调控从三维光场层面被拓宽到了时空维度，本文研究的涡旋空气激射有望使得雷达探测灵敏度提高若干数量级，成为远程激光雷达探测的新途径。

作者贡献

李韩笑：数据结果分析与论文写作；胡悦：实验数据处理。

利益冲突

所有作者声明无利益冲突

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Generation and control of air radiation driven by ultrafast vortex light field

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Abstract

Objective Air radiation providing a cavity-free coherent radiation channel in the atmosphere, is of interest for remote spectroscopy, nonlinear light-matter interaction, and atmosphere-based coherent detection. Femtosecond vortex pulses differ from Gaussian pulses in three coupled aspects: orbital angular momentum (OAM), annular intensity distribution, and phase singularity. These features make vortex fields suitable for regulating strong-field ionization, seed formation, gain evolution, and emission mode simultaneously. The physical role of vortex-field topology in the air radiation generation, however, has not been sufficiently verified experimentally. This work aimed to clarify how an ultrafast vortex field affected the generation of N_2^+ air radiation, whether OAM was transferred from the pump to the lasing signal, and how pump pulse energy and gas pressure influenced the lasing yield under vortex pumping. Another objective was to compare vortex and Gaussian excitation under identical conditions and determine whether the vortex field provided practical advantages in output efficiency and control range.

Methods A Ti: sapphire femtosecond laser system delivered pulses at 800 nm with a pulse duration of 35 fs, a repetition rate of 1 kHz, and a maximum pulse energy of 7 mJ. After attenuation, the beam passed through a circular aperture and a spiral phase plate to form a vortex pump beam carrying OAM. The beam was focused by a lens with a focal length of 20 cm into nitrogen gas to generate forward air radiation near 428 nm. The emitted light was collimated by a second lens. Residual 800 nm pump light and part of the supercontinuum background were removed with dichroic mirrors and band-pass filters. The filtered signal was then recorded with a fiber-coupled spectrometer. To identify the spatial mode and topological charge of the signal, a cylindrical-lens method was used. The output beam was projected onto a CCD camera after passing through the cylindrical lens. The number of slit-like intensity features at the focal plane was used to determine the OAM quantum number.

Results and Discussions The experiments showed that a single femtosecond vortex pump pulse generated stable forward N_2^+ air radiation near 428 nm. The measured spectrum contained two distinct peaks around 428 nm, which were assigned to the P branch and R branch associated with rotational transitions between the $B^2\Sigma_u^+$ ($\upsilon' = 0$) state and the $X^2\Sigma_g^+$ ($\upsilon = 1$) state of N_2^+. This result indicates that the observed radiation was a rotationally resolved coherent air radiation signal rather than ordinary spontaneous fluorescence.

The spatial pattern of the emitted signal is obtained, when the pump beam carried a topological charge of $l = 1$, the signal produced two slit-like features after the cylindrical lens, which corresponds to a topological charge of $l = 2$. The emitted 428 nm air radiation signal therefore carried twice the OAM of the pump. This result provides direct experimental evidence of OAM transfer during the air radiation process. It also shows that the emitted field inherited the phase property of the seed that initiated stimulated amplification.

The observed OAM doubling supports a self-seeding mechanism. The 800 nm vortex pump ionized nitrogen molecules, created the population conditions required for gain in N_2^+, and simultaneously produced a 400 nm second-harmonic seed inside the plasma region. In second-harmonic generation, angular-momentum conservation requires that two pump photons contribute to one harmonic photon. When each pump photon carries one unit of OAM, the generated second-harmonic field carries two units. The 400 nm seed therefore possesses a doubled topological charge and can stimulate the 428 nm transition while preserving the helical phase information. The measured OAM of the lasing signal agrees with this picture.

The yield measurements further showed that the effect of the vortex field depended strongly on the input conditions. At relatively low pulse energy, the annular intensity distribution of the vortex focus reduced the central peak intensity and made population inversion less efficient than in the Gaussian case. Under this condition, Gaussian pumping produced stronger lasing output. As the pump pulse energy increased, the trend reversed. Vortex pumping then generated a higher lasing yield than Gaussian pumping. This behavior is attributed to the different focusing and filamentation characteristics of the vortex beam. The annular profile modifies energy deposition in the plasma and can raise the effective threshold associated with intensity clamping, which allows stronger effective excitation in the gain region. The

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resulting plasma structure becomes more favorable for stimulated amplification.

Pressure-dependent measurements showed a similar tendency. At high input energy, both $l = 1$ and $l = -1$ vortex pumps produced a higher 428 nm lasing yield than the Gaussian beam over a wider pressure interval. The saturation pressure under vortex pumping was also shifted upward by nearly 0.01 MPa relative to the Gaussian case. This shift indicates a broader pressure tolerance and a wider gain-control window. These results demonstrate that vortex-field topology affects not only the output beam mode, but also ionization dynamics, nonlinear frequency conversion, plasma-channel structure, gain build-up, and saturation behavior. The topological degree of freedom therefore acts as an active control parameter in air radiation generation rather than as a passive label of the emitted beam.

Conclusions Ultrafast vortex light fields enable effective generation and control of N_2^+ air radiation. The experiments confirmed that vortex pumping produced 428 nm air radiation with a clear rotational branch structure, a ring-shaped spatial distribution, and definite OAM inheritance. A pump beam with $l = 1$ generated a lasing signal with $l = 2$, which supports the self-seeded amplification mechanism involving second-harmonic generation and demonstrates OAM transfer and conservation in the air radiation process. Comparative measurements also show that vortex pumping has clear advantages over Gaussian pumping in the high-energy regime, including stronger lasing output and higher saturation pressure. These findings establish OAM as a practical control degree of freedom in strong-field ionization, nonlinear conversion, and gain-assisted coherent emission in gases. This work enriches the physical picture of structured-light-controlled air radiation and supports future applications in remote atmospheric sensing, coherent spectroscopy, and quantum-radar-related schemes.

Keywords: vortex light field; air radiation; self-seeded

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