Stable, intense 1 kHz supercontinuum light generation in air

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1 **Introduction**

2 The supercontinuum (SC) light source comes from the nonlinear
3 propagation of ultrafast laser pulses in an optical transparent
4 medium. It is also called “white light” laser when the SC spectrum
5 stretches from the near ultraviolet to the infrared wavelengths. The
6 invention and development of SC [1] has advanced many
7 applications, for instance, in ultrafast laser pulse generation and
8 compression (attosecond pulse) [2], extremely high-precision
9 optical frequency and time metrology [3, 4], terabits/sec high-
10 capacity information communication [5, 6] and ultrafast laser
11 spectroscopy [7, 8] and imaging [9]. Towards the applications, the
12 SC light sources are mostly generated from bulk materials [1, 10]
13 and photonic crystal fibers [11] which limits the SC pulse energy
14 due to the low damage threshold of solid materials. Ultrafast laser
15 filamentation in gases [12-17] is immune from the materials’
16 damage for SC generation. However, the milliseconds time scale of
17 thermal diffusion in an air filament [18-20] leads to air density
18 reduction at the arrival of the next laser pulse for a kHz repetition-
19 rate laser. The thermal self-action effect induces unstable filament
20 beam pointing [21-24] which sets a challenge for high repetition rate
21 filament based SC light source and its applications.

22 In this work, we report a stable, intense, high repetition rate
23 SC generation of a Ti-Sapphire laser through filamentation directly
24 in air. This was accomplished by simply applying an external DC
25 electric field on the filament plasma channel. Through the combined
26 effects of suppression of plasma based thermal deposition [25, 26]
27 and Coulomb interaction, both pointing and intensity jitters of the 1
28 kHz air filament induced SC light were reduced by more than 2 fold.
29 This technique on reducing the thermally induced instability of high
30 repetition rate filaments would work at other filamenting laser
31 wavelengths due to the plasma nature and therefore provides new
32 opportunities for intense stable SC generation and its applications.
33 The stable air filament should directly benefit other filament-based
34 applications, for instance, in remote sensing [8, 27], imaging [28]
35 and micro-machining of condensed materials [29, 30], etc.

36 **Experiment**

Fig.1 Schematic of experimental setups. (a): Generation and characterization of stable high energy SC light in air at high repetition rate. (b): Filament jitter measurement. Real color images of laser filament in air with high voltage off (c) and on (d). The corresponding forward beam patterns on a white screen in real color: (e) high voltage off and (f) high voltage on. Laser pulse energy was 6.12 mJ and the voltage applied on the electrode was 55 kV. The distance between the electrode tip and the laser filament was approximately 0.3 mm. (c) and (d), (e) and (f) have the same length scale, respective.

1 In the experiments, a 1 kHz Ti-sapphire laser was used. It
2 produced 30 fs pulses at 6.12 mJ per pulse. The pulses were focused
3 in air with an $f=50$ cm plano-convex lens as shown in Fig. 1(a).
4 Multiple filaments were produced and the plasma channel was about
5 9cm long (Fig. 1(c)). Meanwhile, three white light spots were
6 generated in the forward direction (Fig. 1(e)). These white light
7 spots were all influenced by the electric field and their jitter
8 trajectories were the same. For the sake of data processing, we chose
9 the top white light spot (marked by the rectangle) because of its
10 more circular shape and higher intensity contrast. When applying a
11 DC voltage of 55 kV on the electrode, laser guided coronas [31, 32]
12 were observed (Fig. 1(d)). They were recorded by the digital camera
13 1 from the top (Fig. 1a). Far field beam patterns at approximately
14 1.2 m to the end of the filament were recorded by the digital camera
15 2 (Nikon D7200, Fig. 1a) as shown in Fig. 1(f). This digital camera
16 operating at 60 fps was also used to monitor the spatial stability of
17 the white light laser spot on the diffusing screen. A focusing lens (2-
18 inches in diameter, $f=6$ cm) set at an angle of 30° to the laser
19 propagation axis imaged the scattered light from the diffusion
20 screen (Fig. 1a) onto a fiber coupled spectrometer (Ocean Optics
21 HR4000) for spectral analysis. A neutral density filter was put in
22 front of the lens to attenuate the diffused intensity. To monitor the
23 filament jitter, an imaging system was constructed as shown in Fig.
24 1(b). A plano-convex lens ($f=20$ cm) was placed at a distance of $2f$
25 after the filament to image it into a laser-triggered high speed
26 camera (PCO. Dimax HS4). The image of the filament was recorded
27 by the high speed camera with the exposure time of 2.5 μ s. The light
28 intensity of the filamenting laser was attenuated before entering the
29 high speed camera by a high reflectivity mirror and several neutral
30 density filters.

32 **Improvement of pointing stability of the SC light source**

33 The spatial positions of the white light laser spots without high
34 voltage were recorded frame by frame (60 fps) as shown in Fig. 2(a).
35 It was obvious that the pointing of white light laser spots from the
36 filament appeared in a large area due to the wandering nature of the

1 high repetition rate filaments [21-24]. Once the DC electric field
 2 was applied near the filament, the white light laser pointing
 3 scattering became smaller (Fig. 2(b)-2(f)) indicating the
 4 improvement of pointing stability. The voltage was tuned from 1 kV
 5 up to 55 kV in the experiment; i.e. the electric field around the
 6 electrode tip changed from about 1.02×10^6 V/m to about 5.61×10^7
 7 V/m; the electric field was obtained by solving the Poisson equation
 8 and Maxwell equation through finite element analysis.

Fig. 2. Maps of forward 300 white light spots without high voltage (a) and under different external DC electric field around the electrode: (b) 2.04×10^6 V/m, (c) 2.55×10^7

1 V/m, (d) 3.06×10^7 V/m (e) 4.59×10^7 V/m, (f) 5.61×10^7 V/m. The statistical average
 2 center of the white light without high voltage is defined as (0, 0).

3 We defined the reference axis as the line between the center
 4 of gravity of each group of white light spots on the screen and the
 5 intersection point between the electrode's pointing direction and the
 6 filament. For the i^{th} group, the length of the reference axis is l_i . The
 7 SC laser scattering angle in the i^{th} group was defined as
 8 $\sigma_{ij} = \frac{1}{l_i} \sqrt{(x_j - \bar{X}_j)^2 + (y_j - \bar{Y}_j)^2}$ with (x_j, y_j) and $(\bar{X}_j, \bar{Y}_j)$ being the
 9 coordinates of the j^{th} white light spot on the screen and the average
 10 coordinates of the j^{th} group white light spots. The standard
 11 deviations (SDEV_{*i*}) of the each group of SC laser scattering angle
 12 were calculated to depict the pointing stability where
 13
$$\text{SDEV}_i = \frac{\sqrt{\sum_{j=1}^N (\sigma_{ij} - \bar{\sigma}_{ij})^2}}{N-1}$$
 with $\bar{\sigma}_{ij} = \frac{1}{N} \sum_{j=1}^N \sigma_{ij}$ being the average of the
 14 group scattering angles of the white light and $N=300$. The pointing
 15 stability of the white light was improved by approximately 2 times
 16 compared to that without electric field and tended to be more stable
 17 when the external DC electric field was increased to a field higher
 18 than about 1×10^7 V/m (Fig. 3). Similar improvement was observed
 19 when negative high voltage was applied to the electrode (red points
 20 in Fig. 3(a)). Moreover, similar results were obtained when the
 21 direction of laser polarization was changed from the vertical to the
 22 horizontal, i.e. the pointing stability improvement of the white light
 23 laser by the electric field was impregnable to the laser polarization
 24 direction. Since the spatial jitter of laser filaments was principally
 25 due to the self-induced thermal heating, the higher the filament
 26 repetition rate was, the stronger the spatial jitter would be at zero
 27 applied voltage (Fig.3 (b)).

28 Thus, the DC electric field control technique could
 29 significantly improve the pointing stability by reducing the spatial
 30 jitters caused by filament self-heating. This was significantly
 31 effective for higher repetition rate, for example, at 1 kHz (Fig. 3(b)).

Fig. 3 (a) SDEV of the SC light forward pointing angle at 1 kHz as a function of the external DC electric field. The SDEVs with DC electric field on were divided by that without DC electric field. (b) SDEV of the SC light forward pointing angle under different laser repetition rates. The SDEVs were normalized to that at 1 kHz laser repetition without DC electric field. (c) SDEV of the filament's local position as a function of the external DC electric field under different laser repetitions. Solid lines are fits for guiding the eyes. (The distance between the electrode tip and the filament was 1mm)

Since the SC laser was generated through filamentation in air, the stable SC laser should originate from the localization of the filament under the external DC electric field. By imaging the filament cross sectional pattern in the high voltage zone using the technique shown in Fig.1 (b), the filament's local position distribution was recorded by the high speed camera synchronized with the laser pulse. By accumulating 7000 shots (6.1mJ/30fs), the SDEV of the filament's local position as a function of the external DC electric field strength is shown in Fig. 3(c). The smaller SDEV of the filament's local position when applying the external field

corroborated the improvement of filament pointing stability in air. Moreover, the filament pointing stability varied with the laser repetition rate (the cases of 0 V/m electric field in Fig. 3d). The jitter of filament pointing was bigger at higher repetition rate due to filament induced self-heating [21-24]. Applying the DC electric field clearly stabilized filament pointing, especially, at higher laser repetition rate. This DC electric field assisted filament pointing stabilization had much less effect at laser repetition rate at or below 100 Hz. The results were in good agreement with the observation in Fig. 2,3a&3b.

Spatial position shift

The spatial pointing position of the white light laser can be tuned by the external DC electric field. Once a positive DC field was applied on the filament, the center of gravity of the SC light beam pattern ‘suddenly’ moved significantly away from the zero field position (Fig. 2b) through Coulomb interaction between the electric field and the filament. Afterwards, when the DC field was further increased, the displacement decreased. As an example, the detailed displacement in the (horizontal) plane containing the electrode and the filament is shown in Fig. 4a (points). We can see that the displacement stabilized (see also Fig. 2c–2f) when the threshold for corona generation ($\sim 2.6 \times 10^6$ V/m) [33] was reached. Numerical simulation based on the Coulomb interaction is in good agreement with the experimental results (Fig. 4(a), solid curve). The displacements of the filament monitored under different electric fields (The distance between the electrode tip and the filament was 1 mm) are shown in Fig. 4(b). The displacement trend of the filament coincided with that of the SC light.

Fig.4 Experimental and numerical results of (a) SC light and (b) filament displacement distance in the (horizontal) plane containing the electrode and the filament under different positive electric fields from initial position (0 V/m). Position '0' represents the initial mean position without the DC electric field and negative displacement is defined as when the filament is closer to the electrode.

Physical interpretation

From the physical point of view, many electrons inside the filament are attracted towards the electrode in the case of positive HV, for example, while the positive ions are pushed away from the filament zone. This would significantly reduce the recombination rate inside the filament; hence, much less thermal jitter of the beam pointing direction. In the case of negative HV, many electrons are pushed away from the electrode while the positive ions move towards the electrode. Again, the recombination rate inside the filament is reduced; hence, thermal jitter of the beam pointing direction is reduced. Moreover, since the improvement of the stability of the white light laser by the electric field is mainly due to the decrease of the recombination between electrons and ions in the electric field, laser polarization state would not affect the charges' spatial distribution. Thus, the improvement of pointing stability of the filament is independent of the laser polarization. Furthermore, the displacement of the filament as a whole with respect to the electrode can be explained as follows. Once a small DC field, positive for example, is applied, some electrons inside the filament will be pulled towards the electrode while the positive charges are repelled. The Coulomb attraction between the positive charges and the electrons will keep the filament intact. The filament as a whole will thus be pulled towards the electrode inducing a sudden change of position of the filament. When the voltage is increased, some more electrons will be pulled out of the filament into the electrode. Consequently, the extra positive charges in the filament will be pushed out of the filament. The plasma density inside the filament will now be lower; hence, the attractive force exerted by the electrode is smaller. The filament displacement is thus smaller. Consequently, the higher the voltage (electric field) is, the smaller the displacement will be (Fig. 4). When corona discharge

(avalanche ionization) starts, the strong plasma at the tip of the electrode will partially shield the field from attracting more electrons into the electrode. Thus, the electric attractive force decreases and the displacement of the filament decreases as the DC electric field increases further. This shielding will stabilize when the avalanche ionization (or plasma density) saturates. Further increase in the voltage will only increase the volume of the ionization (plasma) zone. Consequently, the displacement of the filament stabilizes also (Fig. 4).

Spectral stability

An iris was used to select the white light laser spot out from the whole beam pattern in Fig. 1(e). Fig. 5(a) shows the spectra of white light laser after filamentation with (FIL+55kV) and without (FIL) an external DC electric field. The initial laser spectrum (no FIL) is shown for comparison. The spectra of the FIL and FIL+55kV were significantly broadened compared with that of the pump laser pulse which is due to self-phase modulation (SPM) and self-steepening [1, 15]. The SC bandwidth was further broadened when the external DC high voltage was applied. Due to the SPM caused

by plasma, the frequency change is $\Delta\omega = \frac{2\pi e^2}{cm_e\omega_0} l \frac{\partial[N_e(t)]}{\partial t}$ [13] with e

is electron charge, m_e is electron mass, $N_e(t)$ is the electron density and l is the effective interaction length of the pump pulse in the plasma. Since ionization in the filament can be enhanced by the external electric field through collision ionization [34], the plasma density and the effective interaction length would increase leading to broader bandwidth of the SC. Under each electric field condition, 30 spectral intensity curves were captured. In the i^{th} group, the integrated SC spectral intensity η_{ij} was obtained by integrating spectra intensity from 650 nm to 900 nm, namely $\eta_{ij} = \int I_j d\lambda$ with I_j and λ being the j^{th} spectral intensity and spectral wavelength. The decrease of the SDEV_i of the integrated SC spectra intensities ($\text{SDEV}_i = \sqrt{\sum_{j=1}^N (\eta_{ij} - \overline{\eta_{ij}})^2 / (N-1)}$, $\overline{\eta_{ij}} = \frac{1}{N} \sum_{j=1}^N \eta_{ij}$, $N=30$) as the electric

field increased evidenced the significant improvement by the electric field (more than 3 fold of that without the DC electric field (Fig. 5(b)). The SDEVs were normalized to that at zero electric field. Negative DC field worked better due to the difference in the coupling between the laser filament and the DC electric field. Compared with the positive DC electric field, the filament guided negative corona was confined along the plasma channel and was more stable [32]. By using our approach, 3.55 mJ stable SC pulses at 1 kHz was obtained when the input pump pulses (energy/pulse: 6.54 mJ) underwent filamentation directly in air with a 1m external focusing lens (Fig. 6(c)).

Fig. 5 (a) Typical white light spectra after filamentation with (FIL+55kV) and without (FIL) external DC electric field together with the initial laser spectrum (no FIL) for comparison. Each spectral distribution was normalized at its maximum. (b) Normalized SDEV of the integrated SC spectral intensities when the laser was working at 1 kHz under different polarities (positive and negative) of the DC electric field. The integrated spectral range was from 650 nm to 900 nm. The SDEVs were normalized to that at zero electric field. (c) The SC laser energy obtained as a function of pump laser energy under 1m focusing condition.

Simulation results

1 During femtosecond laser filamentation in air, initially there
2 is a plasma density maximum on the optical axis due to laser
3 instantaneous ionization. Typically, the lifetime of the plasma is
4 within a few nanoseconds time scale in an air filament. The thermal
5 self-heating of laser filament comes mainly from the high field
6 ionization and electron-ion recombination. The long thermal decay
7 time (ms) becomes non-negligible at high laser repetition rate. We
8 have carried out a simulation of the interaction.

9 When an external DC electric field was applied on the laser
10 filament, the effect of the external DC electric field was three fold.
11 Firstly, the laser intensity (Fig. 6(a)) and the plasma density (Fig.
12 6(b)) at the leading and trailing edges of the filament were slightly
13 enhanced, which favored broader SC generation through SPM and
14 self-steepening (Fig. 5(a)). Secondly, the lifetime of the plasma was
15 also significantly extended (Fig. 6(c)). The extended lifetime of the
16 plasma was long enough (around 1 ms) (Fig. 6(d)) to bridge the
17 interval time between two successive pulses. The self-heating effect
18 through plasma recombination would result in air flow near the
19 filament [35, 36], which gave rise to the jitters of filaments and
20 white light lasers. In order to get an insight into the mechanism of
21 air flow near the laser filaments, we simulated numerically the flow
22 fields in 1 ms after the laser pulse. The velocity vector map of the
23 airflow around the filament is shown in Fig. 6(e). The released
24 energy from the plasma recombination heated the ambient air and
25 induced the airflow and vortex around the filament. At both ends of
26 the filament, air vortices emerged and the airflow velocity reached
27 its maximum along the filament propagation path as indicated by
28 the arrows as shown in Fig.6(e). These air disturbances influenced
29 the filament pointing stability. The maximum airflow velocities
30 along the filament propagation axis (e.g. at Point A) by applying
31 different electric fields were calculated as shown in Fig. 6(f). Due
32 to the suppression of the plasma recombination, the airflow velocity

1 decreased quickly as the DC field was switched on and further
2 increased. The consequence is that plasma based thermal energy
3 deposition in air was significantly suppressed. Thus, external DC
4 electric field assisted thermal suppression effect contributes to the
5 stability improvement of the laser filament as well as the filament
6 based white light laser in air. Finally, due to the plasma property of
7 laser filament, external DC electric field provides an extra-control
8 on the spatial localization of laser filament through Coulomb
9 interaction (Fig. 4). All the details of the simulations are provided
10 in the Methods.

11

12

Fig.6 (a), (b) and (c) are the simulated on-axis laser intensity, plasma density and its decay time under different electric fields, respectively. (d) is the simulated plasma lifetime and density as a function of external DC electric field. (e) 2D cross-section of the simulated flow fields around the filament without external electric field. The velocity vectors are colored by velocity magnitude (m/s). The rectangle represents the longitudinal cross section of the cylindrical filament with a length of 200 μm and a diameter of 100 μm . Filament propagated from left to right and was treated as a cylinder in 3D. (f) is the maximum airflow velocity around the filament when applying different electric field. See the details of the simulation in the Methods.

In summary, we have experimentally demonstrated stable SC light source generation through femtosecond laser filamentation in air by applying an external DC electric field on the filament. As the voltage (field) increases, the jittering of the beam decreases while the general pointing direction changes and stabilizes at a field higher than about 1×10^7 V/m. This is principally due to the significant suppression of plasma recombination resulting in less thermal heating of the filament zone. Consequently, both the pointing and the spectral intensity jitters of a 1 kHz SC light are reduced by more than 2 fold. The stable SC pulse with energy of 3.55 mJ at 1 kHz is achieved by using 6.54 mJ filamenting pump pulse directly in air. Our approach solves the current standing problem of high repetition rate filament associated strong jitters. This works at other filamenting wavelengths due to the plasma nature. The findings presented here not only paves a way to generate intense high repetition rate SC light through damage-immune gases and should be beneficial for SC application, but also are crucial and useful for

1 other filament-based applications on remote sensing and remote air
2 lasing, atmospheric analysis, imaging and micromachining of
3 condensed materials etc..

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14 **References**

- 16 [1] Robert R. Alfano, The supercontinuum laser source, 3rd Edition,
17 Springer, (2016) and references therein.
- 18 [2] Thomas Brabec, and Ferenc Krausz, “Intense few-cycle laser
19 fields: frontiers of nonlinear optics”, Rev. Mod. Phys. 72, 545
20 (2000).
- 21 [3] M. Hentschel, R. Klenberger, Ch. Spielmann, G. A. Reider, N.
22 Milosevic, T. Brabec, P. Corkum, U. Heinzmann, M. Drescher,
23 and F. Krausz, “Attosecond metrology”, Nature 414, 509 (2001).
- 24 [4] Th. Udem, R. Holzwarth & T. W. Hänsch, “Optical frequency
25 metrology”, Nature 416, 233-237 (2002).
- 26 [5] S. V. Smirnov, J. D. Ania-Castanon, T. J. Ellingham, S. M.
27 Kobtsev, S. Kukarin, S. K. Turitsyn, “Optical spectral
28 broadening and supercontinuum generation in telecom
29 applications”, Opt. Fiber Tech. 12, 122–147 (2006)
- 30 [6] R. G. H. van Uden, R. Amezcua Correa, E. Antonio Lopez, F.
31 M. Huijskens, C. Xia, G. Li, A. Schülzgen, H. de Waardt, A. M.
32 J. Koonen, & C. M. Okonkwo, “Ultra-high-density spatial

- 1 division multiplexing with a few-mode multicore fibre”, Nature
2 Photon. 9, 965-970 (2014).
- 3 [7] S. A. Kovalenko, A. L. Dobryakov, J. Ruthmann, and N. P.
4 Ernsting, “Femtosecond spectroscopy of condensed phases with
5 chirped supercontinuum probing”, Phys. Rev. A, 59, 2369
6 (1999).
- 7 [8] J. Kasparian, M. Rodriguez, G. Méjean, J. Yu, E. Salmon, H.
8 Wille, R. Bourayou, S. Frey, Y.-B. André, A. Mysyrowicz, R.
9 Sauerbrey, J.-P. Wolf, L. Wöste, “White-light filaments for
10 atmospheric analysis”, Science 301, 61-64 (2003).
- 11 [9] Haohua Tu and Stephen A. Boppart, “Coherent fiber
12 supercontinuum for biophotonics”, Laser & Photon. Rev., 7:
13 629–645 (2013).
- 14 [10] Audius Dubietis, and Arnaud Couairon, *Ultrafast
15 supercontinuum generation in transparent solid-state media*
16 (Springer, 2019).
- 17 [11] John M. Dudley, G. Genty, S. Coen, “Supercontinuum
18 generation in photonic crystal fiber”, Rev. Mod. Phys. 79, 1135
19 (2006)
- 20 [12] S. L. Chin, S. A. Hosseini, W. Liu, Q. Luo, F. Theberge, N.
21 Akozbek, A. Becker, V. P. Kandidov, O. G. Kosareva, and H.
22 Schroeder, "The propagation of powerful femtosecond laser
23 pulses in optical media: physics, applications, and new
24 challenges," Can. J. Phys. **93**, 963-905 (2005).
- 25 [13] A. Couairon and A. Mysyrowicz, "Femtosecond filamentation
26 in transparent media," Phys. Rep. **441**, 47-199 (2007).
- 27 [14] L. Berge, S. Skupin, R. Nuter, J. Kasparian, and J. P. Wolf,
28 "Ultrashort filaments of light in weakly ionized, optically
29 transparent media," Rep. Prog. Phys. **70**, 1633-1713 (2007).
- 30 [15] S. L. Chin, *Femtosecond laser filamentation* (Springer, 2010),
31 Vol. 55.
- 32 [16] S. L. Chin, T. J. Wang, C. Marceau, J. Wu, J. S. Liu, O.
33 Kosareva, N. Panov, Y. P. Chen, J. F. Daigle, S. Yuan, A.
34 Azarm, W. W. Liu, T. Seideman, H. P. Zeng, M. Richardson,
35 R. Li, and Z. Z. Xu, "Advances in intense femtosecond laser

- 1 filamentation in air," Laser Phys. **22**, 1-53 (2012).
- 2 [17] J. P. Wolf, "Short-pulse lasers for weather control," Rep. Prog.
3 Phys. **91**, 34 (2019).
- 4 [18] Y.-H. Cheng, J.K. Wahlstrand, N. Jhajj, and H.M. Milchberg ,
5 The effect of long timescale gas dynamics on femtosecond
6 filamentation, Opt. Express **21**, 4740 (2013)
- 7 [19] N. Jhajj, E.W. Rosenthal, R. Birnbaum, J. K. Wahlstrand, and
8 H. M. Milchberg Demonstration of long-lived high power
9 optical waveguides in air, Phys. Rev. X **4**, 011027 (2014)
- 10 [20] Guillaume Point, Carles Milian, Arnaud Couairon, Andre
11 Mysyrowicz, and Aurelien Houard, "Generation of long-lived
12 underdense channels using femtosecond filamentation in air",
13 J. Phys. B **49**, 094009 (2015)
- 14 [21] V. P. Kandidov and S. A. Shlenov, "Thermal self-action of
15 laser beams and filamentation of pulses in turbulent
16 atmosphere", Atmospheric and Oceanic Optics **25**, 192 (2012).
- 17 [22] J. Yang, T. Zeng, L. Lin, and W. Liu, "Beam wandering of
18 femtosecond laser filament in air", Opt. Express **23**, 25629
19 (2015).
- 20 [23] Elise Schubert, Lorena de la Cruz, Denis Mongin, Sandro
21 Klingebiel, Marcel Schultze, Thomas Metzger, Knut Michel, J.
22 Kasparian, and Jean-Pierre Wolf, "Dual-scale turbulence in
23 filamenting laser beams at high average power", Phys. Rev. A
24 **94**, 043909 (2016).
- 25 [24] N. Jhajj, Y.-H. Cheng, J.K. Wahlstrand, and H.M. Milchberg,
26 Optical beam dynamics in a gas repetitively heated by
27 femtosecond filaments, Opt. Express **21**, 29990 (2013)
- 28 [25] C. G. Durfee III, and H. M. Milchberg, "Light pipe for high
29 intensity laser pulses", Phys. Rev. Lett. **71**, 2409 (1993).
- 30 [26] H. M. Milchberg, T. R. Clark, C. G. Durfee III, and T. M.
31 Antonsen, "Development and applications of a plasma
32 waveguide for intense laser pulses", Phys. Plasmas **3**, 2149
33 (1996).
- 34 [27] Huailiang Xu, Ya Cheng, See-Leang Chin, and Hong-Bo Sun,

1 “Femtosecond laser ionization and fragmentation of molecules
2 for environmental sensing”, *Laser & Photonics Rev.* 9, No. 3,
3 275–293 (2015).

4 [28] Kai Wang, Benjamin D. Strycker, Dmitri V. Voronine, Pankaj
5 K. Jha, Marlan O. Scully, Ronald E. Meyers, Philip Hemmer,
6 and Alexei V. Sokolov, “Remote sub-diffraction imaging with
7 femtosecond laser filaments”, *Opt. Lett.* 37, 1343-1345 (2012).

8 [29] H. Varel, D. Ashkenasi, A. Rosenfeld, M. Wähmer, E.E.B.
9 Campbell, “Micromachining of quartz with ultrashort laser
10 pulses”, *Appl. Phys. A* 65, 367–373 (1997).

11 [30] D. Kiselev, L. Woeste, and J.-P. Wolf, “Filament-induced laser
12 machining (FILM)”, *Appl. Phys. B* 100, 515–520 (2010).

13 [31] Tie-Jun Wang, Yingxia Wei, Yaoxiang Liu, Na Chen,
14 Yonghong Liu, Jingjing Ju, Haiyi Sun, Cheng Wang, Haihe Lu,
15 Jiansheng Liu, See Leang Chin, Ruxin Li, and Zhizhan Xu,
16 “Direct observation of laser guided corona discharges”,
17 *Scientific Reports* 5, 19691 (2015).

18 [32] Tie-Jun Wang, Jianhao Zhang, Zhongbin Zhu, Yaoxiang Liu,
19 Na Chen, Hao Guo, Haiyi Sun, Yuxin Leng, See Leang Chin,
20 and Ruxin Li, “Femtosecond laser filament guided negative
21 coronas”, *AIP Advances* 10, 035129 (2020).

22 [33] W. L. Lama, and C. F. Gallo, “Systematic study of the electrical
23 characteristics of the 'Trichel' current pulses from negative
24 needle-to-plane coronas”, *J. Appl. Phys.*, 45, 103-113 (1974).

25 [34] Yaoxiang Liu, Tie-Jun Wang, Na Chen, Shengzhe Du, Jingjing
26 Ju, Haiyi Sun, Cheng Wang, Jiansheng Liu, Haihe Lu, See
27 Leang Chin, Ruxin Li, Zhizhan Xu, and Zhanshan Wang,
28 “Probing the effective length of plasma inside a filament”. *Opt.*
29 *Express*, 25(10), 11078-11087(2017).

30 [35] Haiyi Sun , Jiansheng Liu, Cheng Wang, Jingjing Ju, Zhanxin
31 Wang, Wentao Wang, Xiaochun Ge, Chuang Li, See Leang
32 Chin, Ruxin Li and Zhizhan Xu, “Laser filamentation induced
33 air-flow motion in a diffusion cloud chamber”, *Opt. Express*,
34 21, 9255 (2013).

35 [36] Jingjing Ju, Tomas Leisner, Haiyi Sun, Aravindan Sridharan,
36 Tie-Jun Wang, Jingwei Wang, Cheng Wang, Jiansheng Liu,
37 Ruxin Li, Zhizhan Xu and See Leang Chin, “Laser-induced

1 supersaturation and snow formation in a sub-saturated cloud
2 chamber”, Appl. Phys. B, 117, 1001-1007(2014)
3

4 **Methods**

5 **Simulation on DC electric field biased filamentation**

6 The nonlinear Schrödinger equation (NLSE) was used to simulate
7 the filamentation process. Input laser pulse was assumed to be an
8 axially symmetrical Gaussian beam. When applying an external DC
9 electric field E on the filament, the envelope of the electric field ε of
10 the input laser beam could be written as [37]

$$11 \quad \varepsilon(r, t, z = 0) = E + \varepsilon_0 \exp(-r^2/w_0^2 - t^2/t_p^2 - ik_0 r^2/2f) \quad (1)$$

12 where $w_0 = w_f(1 + d^2/z_f^2)^{1/2}$ was transverse beam waist at the
13 distance d before the geometrical focus, the initial beam waist was
14 $w_f = 3.5 \text{ mm}$, the laser pulse duration was $t_p = 30 \text{ fs}$, the
15 Rayleigh length was $z_f = \pi w_f^2 n_0 / \lambda_0$, the lens focal length was
16 $f = 50 \text{ cm}$, and the curvature of the laser pulse at the distance d
17 from the linear focus was $f = d + z_f^2/d$. Note that the electric
18 fields at the tip of the electrode in the experiment was not linear.
19 They diverged out for positive voltage and converged in for negative
20 voltage. For simplicity, the E in equation (1) was approximated as
21 the field along the axis of the electrode and all other
22 diverging/converging fields were neglected since the maximum
23 external electric field E (less than 10^9 V/m) in the experiments is
24 approximately 2 orders weaker than the laser electric field ($\sim 10^{10}$
25 V/m). Since the improvement of SC laser pointing stability was
26 independence of the laser polarization in the experiments, the laser
27 polarization direction was set parallel to the electric field and scalar
28 equation was used in the simulation. Simulation started at $d=30 \text{ cm}$
29 before the geometrical focus where no significant ionization
30 occurred.

31 Meanwhile, the NLSE for describing the laser pulse
32 propagation can be expressed as [37]

$$\frac{\partial \mathcal{E}(r,z,t)}{\partial z} = \frac{i}{2k_0} \Delta_{\perp} \mathcal{E} - i \frac{k''}{2} \frac{\partial^2 \mathcal{E}}{\partial t^2} - \frac{\sigma}{2} (1 + i\omega_0 \tau) \rho \mathcal{E} - \frac{\beta_K}{2} I^{K-1} \mathcal{E} + i \frac{\omega_0}{c} n_2 I \mathcal{E} \quad (2)$$

in which k_0, ω_0 were the wave number and angular frequency of the laser beam. The pulse intensity I was $I = c\epsilon_0 n_0 |\mathcal{E}|^2/2$ and the input laser energy in this simulation was 6 mJ. Group velocity dispersion with coefficient $k'' = 2 \times 10^{-29} \text{ s}^2/\text{m}$ [38, 39] was accounted for dispersion. ρ was laser ionized electron density and the collision cross section for inverse bremsstrahlung σ was $\sigma = 2 \times 10^{-24} \text{ m}^2$ [38]. $\beta^K = 1.27 \times 10^{-160} \text{ m}^{17}/\text{W}^9$ [39] was related to multiphoton ionization coefficient, where $K=10$ was the minimum photon number for multiphoton ionization. Nonlinear coefficient n_2 was $3.2 \times 10^{-23} \text{ m}^2/\text{W}$ [39].

The evolution of plasma density distribution can be expressed as [39]

$$\frac{\partial \rho}{\partial t} = \frac{\beta^K}{Kh\omega_0} \left(1 - \frac{\rho}{\rho_{at}}\right) I^K \quad (3)$$

in which h was the Plank constant and $\rho_{at} = 2.7 \times 10^{25} \text{ m}^{-3}$ [39] was the neutral molecule density in air under one standard atmospheric pressure. On the right hand of Eq. (3), multiphoton ionization was taken into account. The averaged characteristic ionization energy E_g for O_2 and N_2 was taken as 14.6 eV [38] in the simulation.

Simulation on plasma decay time in the filament

Under an external DC electric field, dominant processes involved in the wake of plasma channel induced by femtosecond laser pulse include electron-ion recombination, ion-ion recombination, impact ionization, attachments and dissociative attachments of electrons to oxygen molecules. Therefore, time evolutions of electron density n_e , positive ion density n_p , and negative ion density n_n can be described by following equations [40]

$$\begin{cases} \frac{\partial n_e}{\partial t} = \gamma n_e - \eta n_e - \beta_{ep} n_e n_p \\ \frac{\partial n_p}{\partial t} = \gamma n_e - \beta_{ep} n_e n_p - \beta_{np} n_n n_p \\ \frac{\partial n_n}{\partial t} = \eta n_e - \beta_{np} n_n n_p \end{cases} \quad (4)$$

where impact ionization coefficients was $\gamma = \left(\frac{N}{N_0}\right) \frac{5.7 \times 10^9 \alpha^5}{1 + 0.3 \alpha^{2.5}}$ [40].
 N was air density, $N_0 = 2.699 \times 10^{25} \text{ m}^{-3}$, $\alpha = 3.34 \times 10^{-7} E \frac{N}{N_0}$, and
 E was strength of external DC electric field. Attachment coefficient
 of electron to O_2 was $\eta = 2.5 \times 10^7 \text{ s}^{-1}$. The coefficients of
 electron-ion recombination and ion-ion recombination were $\beta_{ep} =$
 $2.2 \times 10^{-13} \text{ m}^3/\text{s}$ and $\beta_{np} = 2.2 \times 10^{-13} \text{ m}^3/\text{s}$, respectively [40].

8

9 Simulation on filament spatial position shift

10 In order to calculate the electric field distribution around the
 11 electrode tip under different voltages, finite element analysis was
 12 used to solve the Poisson equation and the Maxwell equation:

$$13 \quad \nabla(\varepsilon_r \varepsilon_0 \nabla \varphi) = -\rho_V \quad (5)$$

$$14 \quad E = -\nabla \varphi \quad (6)$$

15 where ε_r was the relative dielectric constant, ε_0 was the permittivity
 16 of vacuum, φ was the electric scalar potential, and ρ_V was the
 17 density of volume charges.

18 The plasma filament was assumed to contain N electrons and
 19 positive ions (filament was electrically neutral)). The light electrons
 20 inside the filament tended to move toward the positive electrode,
 21 while the heavy positive ions were pushed slightly away leading to
 22 the charge separation. For simplicity, the distances from the
 23 electrons and positive ions to the electrode tip were l ($\sim 1 \text{ mm}$ in the

1 experiment) and $l+a$, respectively, where a was the diameter of
 2 plasma filament (0.1 mm) as shown in Fig. s2. In the horizontal
 3 plane, electric field lines acting on the filament are in the form of a
 4 fan (green line in Fig.s2.)

5

6 Fig.s2 Schematic diagram of the high voltage electrode controlled filament via the
 7 electric field lines as if it were a fan.

8 According to the Coulomb interaction equation, the force (F)
 9 imposed by the electrode tip (equivalent to point charge Q) on the
 10 plasma filament and the corresponding position change (S) of the
 11 filament were

$$12 \quad F = \frac{Q * N * e}{4\pi \epsilon_r' \epsilon_0 (l)^2} - \frac{Q * N * e}{4\pi \epsilon_r' \epsilon_0 (l + a)^2} \quad (7)$$

$$13 \quad S = \frac{F}{2m} t^2 \quad (9)$$

14 where m was the total mass of nitrogen ion and electron, t was the
 15 lifetime of plasma channel under the external electric field. When
 16 the applied voltage on the electrode was higher than the threshold
 17 for coronas, the electrons inside the plasma filament would be
 18 neutralized by the corona electrode and decreased exponentially as
 19 $N \sim \exp(-U)$, where U was the applied voltage. Initial position of the
 20 filament without applying voltage was defined as '0'. When laser
 21 filament moved closer to the electrode, the position shift value was
 22 negative.

23

Simulation on gas flow field around filament

The filament induced heat flux source was set by user-defined functions (UDF) programmed with C language, which was then interpreted and complied by Fluent 6.3. In the experiments, when the pump laser with 6.12 mJ was focused to generate the air filaments with a diameter of 100 μm and a length of 9 cm, the total deposited energy of the filament (pump laser energy subtracts laser energy after filament) was 1.24 mJ. In the 2D simulation, a uniform energy density inside the filament as in the experiment is under consideration. To reduce the calculation time, the length and diameter of the filament were set as 200 μm and 100 μm , respectively. Besides, the filament was treated as a cylinder in 3D. Then the total deposited energy was estimated to be 2.75×10^{-3} mJ which was the energy to initiate the airflow disturbances. The heating time was assumed to be the same as the plasma lifetime, after which the deposited energy began to thermally diffuse outward. When applying different DC electric fields on the filament, the plasma lifetime was extended and proportional to the DC electric field. As a consequence, plasma recombination based thermal energy deposition in air was significantly suppressed and therefore calculated. The deposited laser energy under the DC electric field was then used to calculate the airflow velocity under the condition.

[37] A. Couairon, E. Brambilla, T. Corti, D. Majus, O. D. Ramirez-Gongora, and M. Kolesik, "Practitioner's guide to laser pulse propagation models and simulation," *Eur. Phys. J.-Spec. Top.* **199**, 5-76 (2011)

[38] A. Couairon, S. Tzortzakis, L. Berge, M. Franco, B. Prade, and A. Mysyrowicz, "Infrared femtosecond light filaments in air: simulations and experiments," *J. Opt. Soc. Am. B-Opt. Phys.* **19**, 1117-1131 (2002).

- 1 [39] Y. Deng, T. Jin, X. W. Zhao, Z. X. Gao, and J. G. Chi,
2 "Simulation of femtosecond laser pulse propagation in air," Opt.
3 Laser Technol. **45**, 379-399 (2013).
- 4 [40] X. M. Zhao, J.-C. Diels, C. Y. Wang and J. M. Elizondo,
5 "Femtosecond ultraviolet laser pulse induced lightning discharges
6 in gases" IEEE J. Quantum Electron. **31**, 599–612 (1995).