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(54) Title: APPARATUS, METHOD AND SYSTEM FOR THE CALIBRATION OF A STREAK CAMERA

(57) Abstract: The present disclosure claims an apparatus, a method and a system for the calibration of a streak camera. A plurality of fiber optic cables is bundled together such that the input ends and the output ends of the fibers are grouped together. Each fiber in the bundle has a distinct and characteristic time taken for light to traverse from the input end to the output end known by the observer. This characteristic time depends on the physical and optical properties of the fibers selected. Calibration light is collected by the fiber input face and travels through the individual fibers in a characteristic time. Individual light pulses will subsequently be detected by the streak camera which converts the time profile of the incoming light pulses into a spatial profile. An observer can compare the observed spatial separation profile to an expected spatial separation profile for calibration.

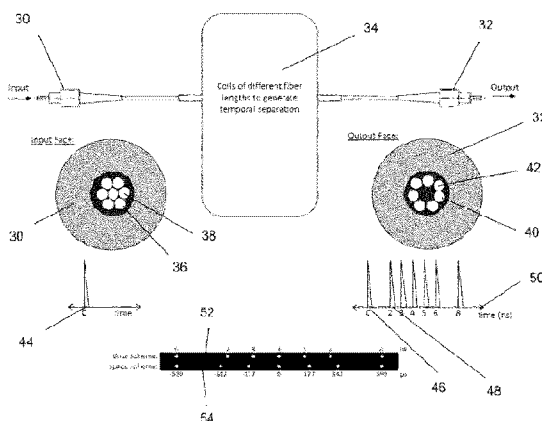


FIGURE 3

APPARATUS, METHOD AND SYSTEM FOR THE CALIBRATION OF A STREAK CAMERA

FIELD OF THE INVENTION

5 The present disclosure relates to an apparatus, method and system for the calibration of streak cameras.

BACKGROUND

10 The streak camera is a high speed time measurement instrument with resolution in the picoseconds to femtoseconds. At a streak camera's entrance slit, incident photons are used to generate electrons that are accelerated through the streak tube towards a phosphor screen. The electrons' trajectories are deflected by a time-varying electric field (sweeping voltage) applied perpendicular to the direction of travel (as shown in Figure 1). As a
15 result, the deflection distance of photoelectrons on the phosphor screen is correlated to the time they arrive at the photocathode.

 The sweep voltage of a streak camera can take the form of a ramp voltage. In many cases, the ramp voltage is not linear (e.g. using the rising or falling edge of a sinusoidal wave) so the accuracy of the temporal
20 measurement of a streak camera relies on careful calibration of the nonlinearity of the shape of the sinusoidal voltage.

 The precision of the temporal measurement in a streak camera depends on the stability of the sweeping voltage. Typical sources of error arise from 1) amplitude variation (vertical axis in **Figure 2**); and 2) phase
25 variation (horizontal variation in **Figure 2**). Current calibration techniques are

expensive, ineffective at the extremes of the sweep range, and require repetitive calibration between observations. A more economical and effective solution to both issues of amplitude and phase variation would provide a more viable and reliable streak camera.

5

SUMMARY

An embodiment of the present disclosure relates to the economic and effective calibration of streak cameras. More specifically, streak cameras use varying electric field generators which oscillate at very high frequencies and aim to record observations over very short and specific time spans. As a result, a high degree of precise calibration is necessary.

The present disclosure discloses an apparatus, a method and a system for the calibration of a streak camera. A plurality of fiber optic cables are bundled together as shown in **Figure 3** such that the input ends and the output ends of the fibers are grouped together. The output face of the fiber bundle is oriented towards the streak cameras observation lens and the input face is oriented away from the device such that it can receive a fraction of the calibration light.

Each fiber in the bundle has a distinct and characteristic time taken for light to traverse from the input end to the output end known by the observer. This characteristic time depends on the length of the fiber, the size of the fiber, and the index of refraction of the medium, in this case the material used to make the fiber, such that the times may be varied by altering the length and the material used in order to produce a desired variety of output times across the plurality of fibers.

The calibration light is collected by the fiber input face and travels through the individual fibers. Light pulses will be emitted from the output face at characteristic times following the desired time profile. The individual light pulses will subsequently be detected by the streak camera and the ejected
5 electrons will be deflected by differing amounts as a result of the varying electric field essentially converting the time parameters of in the incoming light pulses into spatial parameters. An observer can compare the observed spatial separation profile of the light pulses to expected spatial separation profile in order to accurately calibrate for phase variations, amplitude
10 variations, and drift.

An embodiment of an apparatus for calibration of a streak camera comprises:

a fiber bundle, comprising
a plurality of fibers having an input and an output,
15 the plurality of fibers being made of a material selected on a basis of supporting fiber-optic transmission,
wherein the plurality of fibers comprises at least a first fiber and a second fiber,
wherein a light travel time is defined as the time taken for
20 light to travel from the input to the output of the fiber, and
wherein at least one time difference between light travel times is known.

Another embodiment provides a method for calibrating a streak camera comprising:

assembling a fiber bundle comprising a plurality of fibers wherein one end is designated as an input and one end is designated as an output;

forming the plurality of fibers from a material selected on a basis of supporting fibre-optic transmission; and

5 receiving a light pulse into the input of at least two of the plurality of fibers, wherein the light pulse traveling through a first fiber exits the output at a first time and the light pulse traveling through a second fiber exits the output at a second time, and wherein a time difference between said first time and said second time is known.

10 Another embodiment provides a system for calibration of a streak camera comprising:

a fiber bundle, comprising

a plurality of fibers having an input and an output,

the plurality of fibers being made of a material

15 selected on a basis of supporting fibre-optic transmission,

wherein the plurality of fibers comprises at least a first fiber and a second fiber,

wherein a light travel time is defined as the time taken for light to travel from the input to the output of the fiber, and

20 wherein at least one time difference between light travel times is known.

A further understanding of the functional and advantageous aspects of the invention can be realized by reference to the following detailed description and drawings.

25

BRIEF DESCRIPTION OF THE DRAWINGS

Embodiments will now be described, by way of example only, with reference to the drawings, in which:

Figure 1 shows the basic operating principle of a streak camera.

5 **Figure 2** shows a sinusoidal sweeping scheme at a 40MHz repetition rate.

Figure 3 shows a reference fiber bundle design.

DETAILED DESCRIPTION

10 Various embodiments and aspects of the disclosure will be described with reference to details discussed below. The following description and drawings are illustrative of the disclosure and are not to be construed as limiting the disclosure. The drawings are not necessarily to scale. Numerous specific details are described to provide a thorough understanding of various
15 embodiments of the present disclosure. However, in certain instances, well-known or conventional details are not described in order to provide a concise discussion of embodiments of the present disclosure.

As used herein, the terms, “comprises” and “comprising” are to be construed as being inclusive and open ended, and not exclusive. Specifically,
20 when used in this specification including claims, the terms, “comprises” and “comprising” and variations thereof mean the specified features, steps or components are included. These terms are not to be interpreted to exclude the presence of other features, steps or components.

As used herein, the term “exemplary” means “serving as an example, instance, or illustration,” and should not be construed as preferred or advantageous over other configurations disclosed herein.

As used herein, the terms “about” and “approximately”, when used in conjunction with ranges of dimensions of particles, compositions of mixtures or other physical properties or characteristics, are meant to cover slight variations that may exist in the upper and lower limits of the ranges of dimensions so as to not exclude embodiments where on average most of the dimensions are satisfied but where statistically dimensions may exist outside this region. It is not the intention to exclude embodiments such as these from the present disclosure.

Figure 1 depicts a common embodiment of a modern streak camera. The 1D fiber array **12** provides a one (1) dimensional source of observable light. The camera is positioned such that light emitted by the fiber array is isolated through the input slit **14** of the streak camera. The light pulses interact with a photocathode **16** such that electrons are ejected from the interaction sites of the photons and the photocathode towards the capture screen **22**. In a preferred embodiment, the screen is a phosphor screen for electron absorption. Before being absorbed at the capture screen **22**, electrons interact with a deflection region and are deflected by a time varying potential created and varied by the potential manipulating devices **20**. In a preferred embodiment, the sweep voltage **24** controlled by the potential manipulating devices **20**, is linearly changing. However, in practice, a sinusoidal varying potential is more common.

Figure 2 depicts the deflection ranges of electrons deflected at different times relating to the sinusoidal sweep voltage. Although a linear regression would model a sine wave very well near the center of the period **26** (i.e. the average voltage) the loss of accuracy falls off dramatically near the edges **28** (i.e. the maximum and minimum voltages).

In many applications (e.g. fluorescence lifetime), the system's temporal response which includes the laser excitation pulse width and the stretching of the pulse by the optical system is not negligible and it would be useful to have this accounted for. The present design allows the measure of the system input response, which is particularly useful in deconvolution of fluorescence lifetime in which the excitation laser pulse is measured directly, and simultaneously for each fluorescence decay. In most applications, the system response is measured using the same setup but only before or after the fluorescence decay, not at the same time. The advantages of simultaneous system response measurement is to account for potential pulse to pulse variability (e.g. from the excitation laser and the measurement system).

<u>Screen Size / Sweep Range</u>	<u>Sweep voltage crossing time (ns)</u>	<u>Sweep Rate (ps/mm)</u>		<u>Linearity (center rate / edge rate)</u>
		<u>Center of screen</u>	<u>Edge of screen</u>	
6.1%	0.5	25.00	25.04	99.8%
12.3%	1.0	50.00	50.38	99.2%
24.5%	2.0	100.0	103.2	96.9%
49.0%	4.1	200.0	229.5	87.1%
98.1%	10.9	400.0	2061	19.4%

Table 1

20

Table 1 shows the sweep voltage crossing time and time-scale linearity for various screen size to sweep range ratios, given a sweep frequency of

40MHz. The sweep rate is calculated based on a screen size of 19.5mm.

These settings are representative of the modes available to the Optronis SC10 streak camera, though the 400.0ps/mm setting is a custom option.

5 The sweep voltage of the streak camera, operating at 40MHz at a high voltage, is difficult to keep stable. The amplitude of the sweep voltage typically requires 2 hours to stabilize to the proper value. Also, the phase difference between the input trigger to the sweep unit and the sweep voltage drifts over time as the streak camera is running.

10 As a result of the sweep voltage amplitude drift, it is insufficient in practice to rely on expected values of the sweep voltage amplitude. Furthermore, to prevent the fluorescence decays from drifting off-screen over time due to the continuous phase delay, a real-time correction to the phase delay must be applied.

A solution to both these problems is proposed by the present
15 disclosure. In an embodiment of the disclosure, reference fibers of known varying lengths are bundled together. Calibration light is collected at the input end of these fibers and is transmitted out the output end of the bundle. Light pulses will exit the output at known times related to the time taken for the light to propagate through each one of the fibers in the fiber bundle. These signals
20 are then processed through the streak camera's varying potential field, effectively converting their separation from a temporal dimension to a spatial dimension based on the changing electron deflection angles. The spatial profile of the observed calibration light pulses is compared to a known calibration profile in order to correct for unwanted drift, amplitude variation and
25 phase variation. One advantage of this design is that calibration is be done at

the same time as each observation is made and can accounts for (and correct) variations between each observation.

The time taken **T** for light to traverse an entire fiber follows the optics equation (1):

$$T = \frac{c}{n} * l \quad (1)$$

5 where **c** is the speed of light in a vacuum, **n** is the index of refraction of the medium (in this case the material used as a fiber) and **l** is the length of the fiber.

An embodiment of the present disclosure comprises a fiber bundle wherein seven fibers of different lengths are used to generate different arrival
10 times at the streak camera. The fibers are illuminated by back reflected excitation light, are free-space coupled into a single fiber, and then connected into the streak camera's reference port. As a result, at the top of the streak camera readout, a constant pattern of 7 spots appears of known separation in time. This scheme is shown in **Figure 3**. It is noted that the fibers in the
15 bundle may be either single and multi-mode, however, practically, it is much easier to use multi-mode fibers.

Specifically, **Figure 3** shows a reference fiber bundle design for a streak camera produced in accordance with the present disclosure. Seven fibers collect back reflected excitation light at the input end **30**. Each fiber has
20 a known different length, to generate separation in the arrival time of each channel at the output end **32**. For example, a first fiber **36** and a second fiber **38** simultaneously collect light at the input face **30**. The second fiber **38** has a known difference in length from the first fiber **36**. The fibers are bundled together in the fiber bundle **34**. Light propagates through both fibers and are

emitted from the output face **32**. The output is free-space coupled into a single fiber, and connected to the reference port of the streak camera. The input laser pulse is shown on a time scale **44** representing the unity of input light. The output laser pulse profile is shown on a time scale **50** representing the separation of time between output pulses traveling through different fibers. Following the above mentioned example, the pulse exiting the first fiber **46** and the pulse exiting the second fiber **48** are shown on the output time scale **50**. The separation in time **52** is converted to a separation in space **54** by the streak camera, resulting in the space scheme at the bottom of the figure.

Another embodiment of the present disclosure comprises a plurality of fibers of identical length in a fiber bundle. Each fiber's material is selected such that a desired light output time profile is produced. This is achieved by selecting materials with incrementally increasing indices of refraction.

A more general embodiment of the present disclosure comprises varying the lengths and the materials used in the fibers to produce a desired output profile.

It is favorable for the abovementioned embodiment to have output fibers evenly positioned about a circle as shown in **Figure 3** at a constant radial distance from the center of the output face such that light intensity from surrounding fibers is evenly distributed.

The specific embodiments described above have been shown by way of example, and it should be understood that these embodiments may be susceptible to various modifications and alternative forms. It should be further understood that the claims are not intended to be limited to the particular

forms disclosed, but rather to cover all modifications, equivalents, and alternatives falling within the spirit and scope of this disclosure.

THEREFORE WHAT IS CLAIMED IS:

1. An apparatus for calibration of a streak camera comprising:
 - a fiber bundle, comprising
 - a plurality of fibers having an input and an output,
 - the plurality of fibers being made of a material selected on a basis of supporting fiber-optic transmission,
 - wherein the plurality of fibers comprises at least a first fiber and a second fiber,
 - wherein a light travel time is defined as the time taken for light to travel from the input to the output of the fiber, and
 - wherein at least one time difference between light travel times is known.
2. The apparatus as claimed in claim 1, wherein the first fiber has a different length than the second fiber.
3. The apparatus as claimed in claim 2, wherein the time difference is related to a difference of lengths between the first fiber and the second fiber.
4. The apparatus as claimed in any one of claims 1 to 3, wherein the first fiber has at least one of a difference of index of refraction and a difference in optical properties than the second fiber.

5. The apparatus as claimed in claim 4, wherein the time difference is related to a velocity difference between velocities of light through the first fiber and the second fiber.
6. The apparatus as claimed in any one of claims 1 to 5, wherein the input face is positioned to receive calibration light.
7. The apparatus as claimed in any one of claims 1 to 6, wherein the output face is positioned to output light into the streak camera for calibration.
8. The apparatus as claimed in claim 7, wherein a plurality of output signals exiting the output face at known times are converted by a streak camera from a time separation profile to a space separation profile characterized by the changing electric field produced by the streak camera.
9. The apparatus as claimed in claim 8, wherein the space separation profile can be compared to an expected space separation profile based on the characteristics of the fiber bundle in order to correct for one or more of phase variation error, amplitude variation error and potential drift.
10. The apparatus as claimed in claim 9, wherein the fiber bundle comprises seven fibers and wherein a comparison between the space separation profile produced by the streak camera and the expected space separation profile is used to calibrate for phase variation error and amplitude variation error in a single observation.

11. The apparatus as claimed in any one of claims 1 to 10 wherein the fibers at the output are evenly positioned about a circle with a chosen radial distance from the center of the output.

12. A method for calibrating a streak camera comprising:
assembling a fiber bundle comprising a plurality of fibers wherein one end is designated as an input and one end is designated as an output;
forming the plurality of fibers from a material selected on a basis of supporting fibre-optic transmission; and
receiving a light pulse into the input of at least two of the plurality of fibers, wherein the light pulse traveling through a first fiber exits the output at a first time and the light pulse traveling through a second fiber exits the output at a second time, and wherein a time difference between said first time and said second time is known.

13. The method as claimed in claim 12, wherein the first fiber has a different length than the second fiber.

14. The method as claimed in claim 13, wherein the time difference is related to a difference of lengths between the first fiber and the second fiber.

15. The method as claimed in any one of claims 12 to 14, wherein the first fiber has at least one of a difference of index of refraction and a difference in optical properties than the second fiber.

16. The method as claimed in claim 15, wherein the time difference is related to a velocity difference between velocities of light through the first fiber and the second fiber.

17. The method as claimed in any one of claims 12 to 16, wherein the input face is positioned to receive back reflected excitation light.

18. The method as claimed in any one of claims 12 to 17, wherein the output face is positioned to output light into the streak camera for calibration.

19. The method as claimed in claim 18, wherein a plurality of output signals exiting the output face at known times are converted by a streak camera from a time separation profile to a space separation profile characterized by the changing electric field produced by the streak camera.

20. The method as claimed in claim 19, wherein the space separation profile can be compared to an expected space separation profile based on the characteristics of the fiber bundle in order to correct for one or more of phase variation error, amplitude variation error and potential drift.

21. The method as claimed in claim 20, wherein the fiber bundle comprises seven fibers and wherein a comparison between the space separation profile produced by the streak camera and the expected space separation profile can be used to calibrate for phase variation error and amplitude variation error in a single observation.

22. The method as claimed in any one of claims 12 to 21 wherein the fibers at the output are evenly positioned about a circle with a chosen radial distance from the center of the output.

23. A system for calibration of a streak camera comprising:
a fiber bundle, comprising
a plurality of fibers having an input and an output,
the plurality of fibers being made of a material
selected on a basis of supporting fibre-optic transmission,
wherein the plurality of fibers comprises at least a first
fiber and a second fiber,
wherein a light travel time is defined as the time taken for
light to travel from the input to the output of the fiber, and
wherein at least one time difference between light travel
times is known.

24. The system as claimed in claim 23, wherein the first fiber has a different length than the second fiber.

25. The system as claimed in claim 24, wherein the time difference is related to a difference of lengths between the first fiber and the second fiber.

26. The system as claimed in any one of claims 23 to 25, wherein the first fiber has at least one of a difference of index of refraction and a difference in optical properties than the second fiber.

27. The system as claimed in claim 26, wherein the time difference is related to a velocity difference between velocities of light through the first fiber and the second fiber.

28. The system as claimed in any one of claims 23 to 27, wherein the input face is positioned to receive back reflected excitation light.

29. The system as claimed in any one of claims 23 to 28, wherein the output face is positioned to output light into the streak camera for calibration.

30. The system as claimed in claim 29, wherein a plurality of output signals exiting the output face at known times are converted by a streak camera from a time separation profile to a space separation profile characterized by the changing electric field produced by the streak camera.

31. The system as claimed in claim 30, wherein the space separation profile can be compared to an expected space separation profile based on the characteristics of the fiber bundle in order to correct for one or more of the following: phase variation error, amplitude variation error and potential drift.

32. The system as claimed in claim 31, wherein the fiber bundle comprises seven fibers and wherein a comparison between the space separation profile produced by the streak camera and the expected space separation profile is used to calibrate for phase variation error and amplitude variation error in a single observation.

33. The system as claimed in any one of claims 23 to 32 wherein the fibers at the output are evenly positioned about a circle with a chosen radial distance from the center of the output.

34. A streak camera, wherein said streak camera has a calibration device comprising

a fiber bundle, comprising

a plurality of fibers having an input and an output,

wherein the input is oriented towards an

observable and the output is oriented towards the streak camera,

the plurality of fibers being made of a material

selected on a basis of supporting fibre-optic transmission,

wherein the plurality of fibers comprises at least a first fiber and a second fiber,

wherein a light travel time is defined as the time taken for light to travel from the input to the output of the fiber, and

wherein at least one time difference between light travel times is known.

35. The apparatus as claimed in claim 34, wherein the first fiber has a different length than the second fiber.

36. The apparatus as claimed in claim 35, wherein the time difference is related to a difference of lengths between the first fiber and the second fiber.

37. The apparatus as claimed in any one of claims 34 to 36, wherein the first fiber has at least one of a difference of index of refraction and a difference in optical properties than the second fiber.

38. The apparatus as claimed in claim 37, wherein the time difference is related to a velocity difference between (group) velocities of light through the first fiber and the second fiber.

39. The apparatus as claimed in any one of claims 34 to 38, wherein the input face is positioned to receive back reflected excitation light.

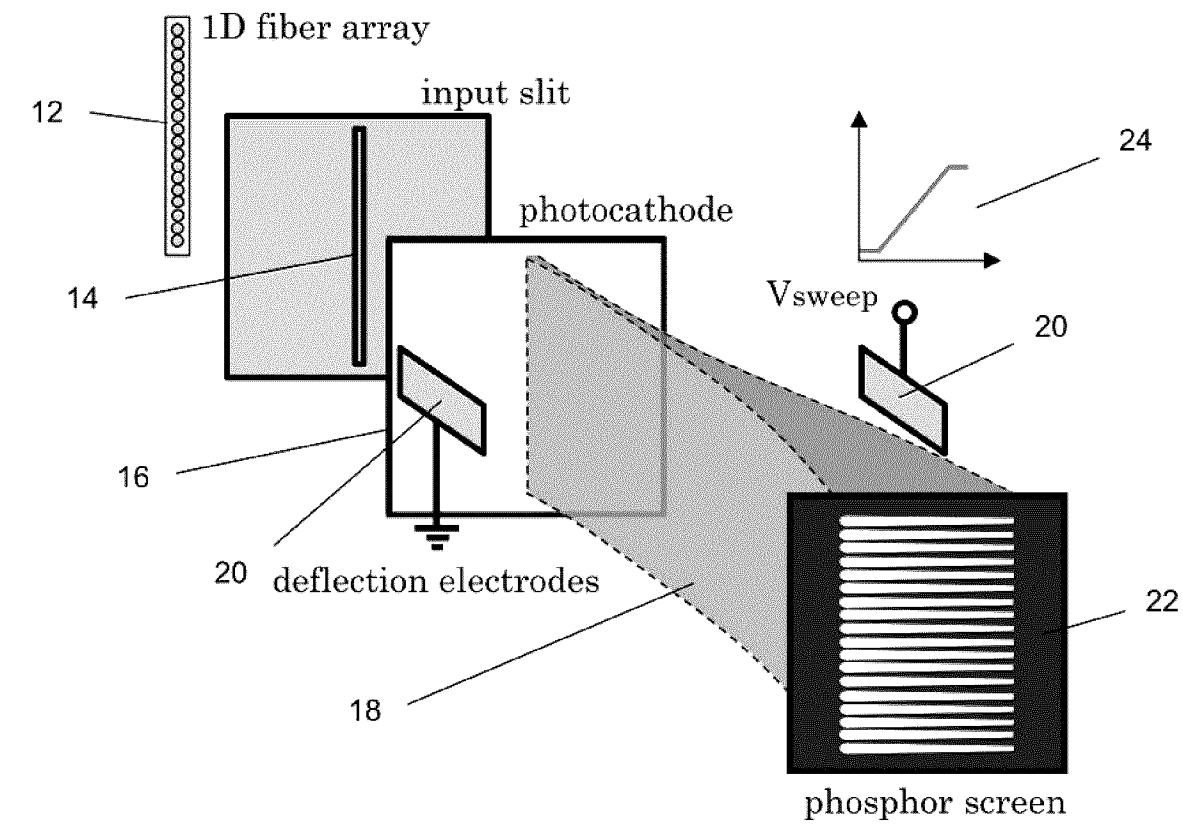
40. The apparatus as claimed in any one of claims 34 to 39, wherein the output face is positioned to output light into the streak camera for calibration.

41. The apparatus as claimed in claim 40, wherein a plurality of output signals exiting the output face at known times are converted by a streak camera from a time separation profile to a space separation profile characterized by the changing electric field produced by the streak camera.

42. The apparatus as claimed in claim 41, wherein the space separation profile is compared to an expected space separation profile based on the characteristics of the fiber bundle in order to correct for one or more of phase variation error, amplitude variation error and potential drift.

43. The apparatus as claimed in claim 42, wherein the fiber bundle comprises seven fibers and wherein a comparison between the space separation profile produced by the streak camera and the expected space separation profile is used to calibrate for phase variation error and amplitude variation error in a single observation.

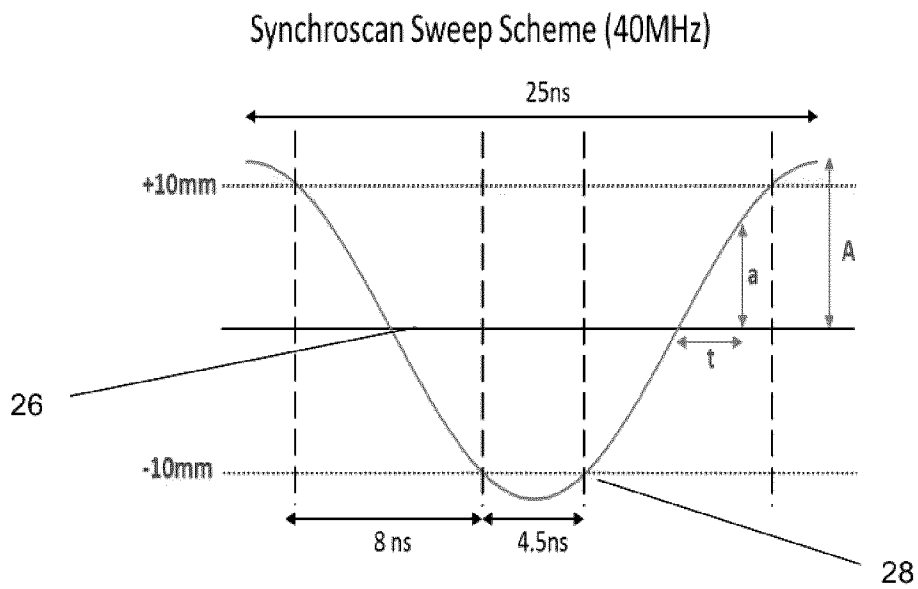
44. The apparatus as claimed in any one of claims 34 to 43 wherein the fibers at the output are evenly positioned about a circle with a chosen radial distance from the center of the output.



PRIOR ART

FIGURE 1

2/3



Sweep Voltage Follows:

$$a = A \sin\left(2\pi \frac{t}{T}\right) \rightarrow A = \frac{a}{\sin\left(2\pi \frac{t}{T}\right)}$$

FIGURE 2

3/3

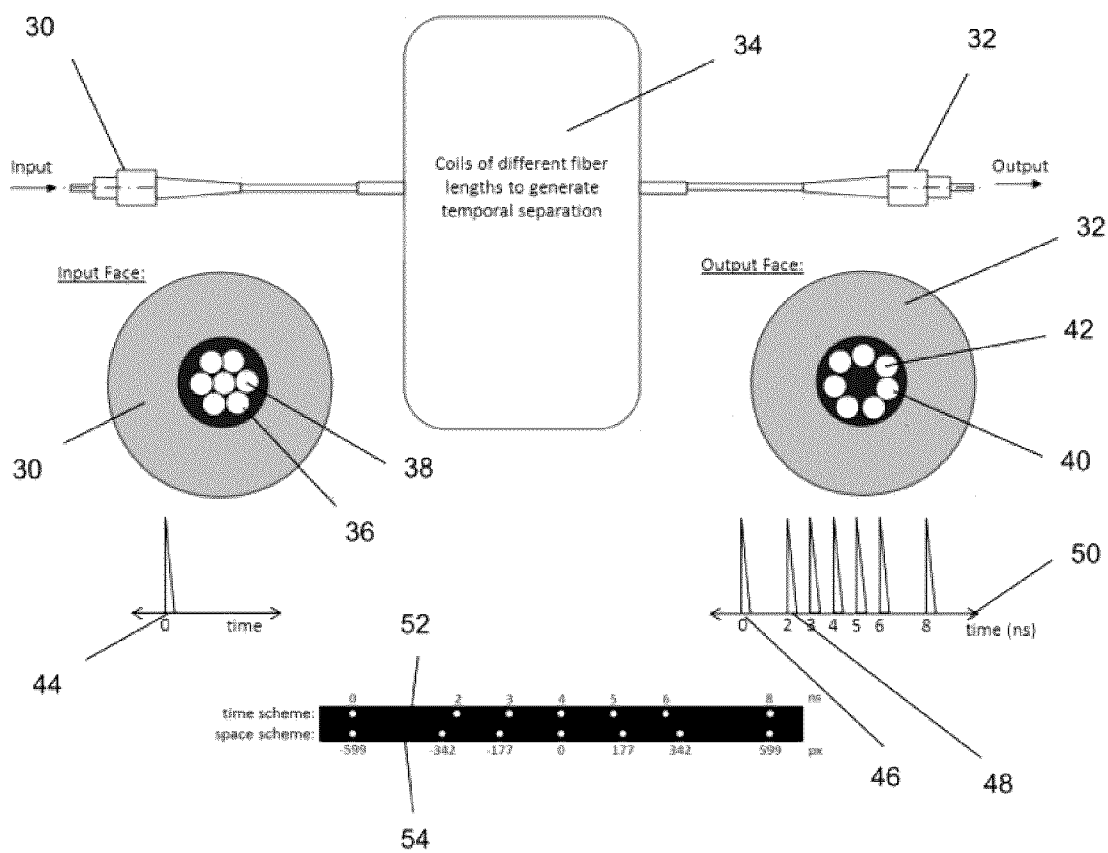


FIGURE 3

INTERNATIONAL SEARCH REPORT

International application No.

PCT/CA2014/050743

A. CLASSIFICATION OF SUBJECT MATTER

IPC: **G04F 13/02** (2006.01), **G01J 1/08** (2006.01), **G02B 6/04** (2006.01), **H01J 31/54** (2006.01)

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

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Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic database(s) consulted during the international search (name of database(s) and, where practicable, search terms used)

Canadian Patent Database, WEST, Google

Keywords: calibration, streak camera, fiber optic, spatial/time separation, profile, phase/amplitude variation/error

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US4435727A; SCHILLER et al. ; 06 March 1984 (06-03-1984) Abstract; [col. 1 lines 35-42]; [col. 3 lines 55-59]; [col. 4 lines 12-30]	1-8, 12-19, 23-30, 34-41
A	EP0478458A1; GONTIER et al.; 01 April 1992 (01-04-1992) **** whole document ***	1-44
A	US6642499B1; BONI et al.; 04 November 2003 (04-11-2003) **** whole document ***	1-44
A	"Technique for Optically Calibrating Streak Cameras"; Terence J. Davies; Review of Scientific Instruments; vol. 41, p.920 (1970) **** whole document ***	1-44

☒ Further documents are listed in the continuation of Box C.☒ See patent family annex.

* "A" "E" "L" "O" "P"	Special categories of cited documents: document defining the general state of the art which is not considered to be of particular relevance earlier application or patent but published on or after the international filing date document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified) document referring to an oral disclosure, use, exhibition or other means document published prior to the international filing date but later than the priority date claimed	"T" "X" "Y" "&"	later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art document member of the same patent family
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Date of the actual completion of the international search
08 December 2014 (08-12-2014)Date of mailing of the international search report
15 December 2014 (15-12-2014)Name and mailing address of the ISA/CA
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INTERNATIONAL SEARCH REPORT

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C (Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT		
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	"Compact optical technique for streak camera calibration" ; BELL et al.; Review of Scientific Instruments; vol. 75, p.3930 (2004)	1-44

INTERNATIONAL SEARCH REPORT
Information on patent family members

International application No.

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Patent Document Cited in Search Report	Publication Date	Patent Family Member(s)	Publication Date
US4435727A	06 March 1984 (06-03-1984)	None	
EP0478458A1	01 April 1992 (01-04-1992)	EP0478458A1 FR2667394A1 FR2667394B1	01 April 1992 (01-04-1992) 03 April 1992 (03-04-1992) 08 October 1993 (08-10-1993)
US6642499B1	04 November 2003 (04-11-2003)	None	