Ministero dello Sviluppo Economico

Ricevuta di presentazione

per

Brevetto per invenzione industriale

Domanda numero: 102020000010357

Data di presentazione: 08/05/2020

DATI IDENTIFICATIVI DEL DEPOSITO

Ruolo	Mandatario
Depositante	Marco Santo Pietro Celestino
Data di compilazione	08/05/2020
Riferimento depositante	B10/1399
Titolo	APPARATO PER TOMOGRAFIA OTTICA A COERENZA DI FASE
Carattere domanda	Ordinaria
Esenzione	NO
Accessibilità al pubblico	NO
Numero rivendicazioni	10
Autorità depositaria	

PRIVACY

Autorizzo il trattamento dei dati personali, inseriti all'interno del deposito, ai sensi del GDPR (Regolamento UE 2016/679) e del Decreto Legislativo 30 giugno 2003, n. 196 "Codice in materia di protezione dei dati personali"

RICHIEDENTE/I

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Quota percentuale	5.0%

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CLASSIFICAZIONI

Sezione	Classe	Sottoclasse	Gruppo	Sottogruppo

NUMERO DOMANDE COLLEGATE

DOCUMENTAZIONE ALLEGATA

Tipo documento	Riserva	Documento
Riassunto in Inglese	NO	B10_1399 Riassunto in inglese.pdf.p7m hash: 19356d1d620acfce65fc60f0442f3da2
Descrizione in inglese	NO	B10_1399 Descrizione in inglese.pdf.p7m hash: e03d7d515bb82da615d83da90e6c1ec2
Disegni	NO	B10_1399 Disegni in italiano e in inglese.pdf.p7m hash: 377df755801f7e1404f749254c799741
Rivendicazioni in inglese	NO	B10_1399 Rivendicazioni in inglese.pdf.p7m hash: d181f59d07c41dd079ab3d6eb0963c53
Rivendicazioni	SI	hash:
Riassunto	SI	hash:
Lettera di Incarico	SI	hash:
Descrizione in italiano*	SI	hash:

PAGAMENTI

Tipo	Identificativo	Data

Bollo	01181474620760	23/08/2019

DOVUTO

Gli importi indicati non tengono conto delle eventuali esenzioni applicabili

Importo Tasse:	€ 50,00
Importo Imposta Bollo:	€ 20,00

NOTE

Descrizione in lingua inglese dell'invenzione industriale dal titolo "APPARATO PER TOMOGRAFIA OTTICA A COERENZA DI FASE" ("OPTICAL COHERENCE TOMOGRAPHY APPARATUS") a nome di:

CNIT - Consorzio Nazionale Interuniversitario per le Telecomunicazioni, con sede a Parma;

Scuola superiore di studi universitari e di perfezionamento Sant'Anna, con sede a Pisa;

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DESCRIZIONE - DESCRIPTION

Field of the invention

[0001] The present invention relates to an improved optical coherence tomography (OCT) apparatus, in particular, for diagnostic procedures involving a patient's tissue such as the wall of a biological lumen of a patient's body, for example intra-vascular applications (IV-OCT).

Related art and technical problems

[0002] Optical coherence tomography is a non-invasive and non-contact imaging technique using light to take cross-sectional and three-dimensional images from within a biological tissue. At first, OCT was mainly used to investigate human retina and in some intra-vascular applications and, more recently, also in dermatology, gastroenterology and urology.

[0003] In OCT, light waves emitted by broadband light source are split into a reference beam and a sample beam. The latter is directed within the tissue and backscattered by internal tissue microstructures. The backscattered light is caused to interfere with the reference beam, and the obtained interference pattern is used to measure the light echoes versus the depth profile of the tissue.

[0004] The most important improvements provided by OCT over such imaging methods as X-ray computed tomography, magnetic resonance and ultrasound-based techniques are related to axial resolution, i.e. A-resolution, mainly due to the use of optical frequency domain. At present, micrometre axial resolutions up to about 10-20 µm can be easily obtained.

[0005] Concerning IV-OCT, this has become one of the most preferred techniques to image coronary arteries for analysis of atherosclerotic plaques and guidance of semi-invasive interventional procedures of percutaneous coronary intervention such as angioplasty and stenting.

[0006] As shown in Fig. 1A, during these procedures, an OCT image wire or cable 40 is inserted and caused to advance from a vascular entry site 3 up to a target region 2_l of a portion of interest 8 of a blood vessel 1 such as an artery with or without a synthetic graft, over a conventional angioplasty guide-wire, not shown. This way, an optical beam 11 generated by an optical source beam 10 can reach target region 2_l through cable 40 and a submillimetre probe 60 arranged at a distal end of cable 40.

[0007] In order to obtain a given axial resolution (resolution through the tissue), a usually continuous light wavelength sweep or scan 9λ is carried out, which can be schematically represented as a succession of R optical beams of respective wavelengths λ_k, $k=1…R$ varying over a predetermined wavelength range Λ are sent to a target sector $2_{j,l}$ forming target region 2_l, as shown in Fig. 1B during a wavelength scan time T_λ, see also Fig. 1C, thus obtaining an axial line $97_{j,l}$ of target sector $2_{j,l}$.

[0008] Moreover, in order to obtain a 2D visualization, i.e. a cross-section image 98_l of target region 2_l, a radial 360° scan (B-scan) 9β on the surrounding arterial wall is performed by a mechanically rotating beam deflection means of probe 60, not shown. In other words, wavelength scan 9λ is repeated for each of M target sector $2_{j,l}$ j=1…M, and axial lines $97_{j,l}$ j=1…M are used to reconstruct 2D cross-section image 98_l. Therefore, the time required to obtain cross-section image 98_l of target region 2_l is at least $M \cdot T_\lambda$. As described more in detail hereinafter, in the current state of the art, the maximum speed of radial scan 9β allowed by the deflection means currently in use is far slower than the speed wavelength scan 9λ allowed by currently available optical beam sources 10.

[0009] Finally, a usually concomitant pullback translation 9z of the probe along the portion of interest 8 is also carried out to generate a 3D volumetric data set including comprehensive microstructure information of the wall of the artery or synthetic graft 1. In other words, radial scan 9β is repeated for each of S axial positions, i.e. target regions 2_l l=1…S, and 2D cross section 98_l l=1…S are merged to form a 3D image 99 of portion of interest 8.

[0010] In this connection, significant sensitivity improvements, up to final sensitivity values higher than 120dB, have been possible through higher-performance Fourier-domain techniques (FD-OCT) based on a swept-source (SS-OCT). In this case, the continuous wave source is periodically swept in time in the typically ca. 100nm-wide wavelength range of interest at a speed at least two order of magnitude faster than the radial scan.

[0011] However, despite the improvements summarized above, currently available OCT equipment still shows some important performance limitations.

[0012] A first issue is a limited axial penetration depth, i.e. a poor penetration capacity through the tissue under test, normally not exceeding about 1.5 mm, which is mainly due to strong light backscattering and high absorption coefficients within the tissues and the blood. In particular, the low axial penetration is a real drawback when observing of a blood vessel that has been significantly remodelled due to plaque burden. In this case, the outline of the true lumen disappears on the OCT image and the interventionist must preliminarily connect the dots in his/her mind as to the extent of the plaque.

[0013] Further drawbacks are related to the use of mechanical moving components to perform radial scan 9β. In particular, rotating mirrors are normally used as beam deflection means, allowing a speed limited to a few hundreds of Hz, or motorized translators.

[0014] Firstly, the scan rate cannot exceed a mechanically attainable value, which is a limitation, in particular, when observing rapidly moving tissues. Faster scanning systems are known based on MEMS, galvomirrors or piezoelectric actuators, but these solutions still comprise mechanical parts, along with electrical supply means placed nearby the scanning region, which, due to their encumbrance, could not be enclosed within a submillimetre endoscope generally used in a medical context.

[0015] Secondly, the vibrations induced by the moving components limit the available signal-to-noise ratio (SNR), and lead therefore to relatively poor reliability and sensitivity.

[0016] Thirdly, it is not easy to fit mechanically rotating components into such a small device as an intra-vascular probe.

[0017] Even the achieved sensitivity of SS-OCT systems has some drawbacks in the case of specific IVOCT applications, since it contributes to limit the maximum penetration depth to above 1.5 mm.

Summary of the invention

[0018] It is therefore an object of the present invention to provide an OCT apparatus, in particular, for intravascular applications, having a higher axial penetration depth than currently available OCT technology.

[0019] It is another feature of the invention to provide an OCT apparatus, typically an IV-OCT apparatus, in which no moving parts are used to carry out a 360° scan of an optical beam to direct it against the inner wall of a biological lumen such as a blood vessel, so as to overcome the above limitations due to mechanically rotating components.

[0020] It is a particular feature of the invention to provide an FD-OCT apparatus comprising a continuous-wave swept-source (SS-OCT).

[0021] These and other objects are achieved by an apparatus according to independent claims n. 1 and 4. Exemplary embodiments and modifications of the apparatus are defined by the dependent claims.

[0022] A diagnostic apparatus for performing an optical coherence tomography of a target region of a patient’s body tissue comprises:

- an optical beam source configured to emit an optical beam;
- an optical cable having a proximal end in communication with the optical beam source to receive the optical beam therefrom, and a distal end arranged to be introduced into the target region;
- a beam steering device configured to
  - steer the optical beam at a plurality of beam rotation angles with respect to an angular reference position integral to the optical cable, in a predetermined radial scan time, so as to

obtain a plurality of respective steered optical beams, and to direct the steered optical beams sequentially in said radial scan time towards a plurality of respective target sectors of the target region;

  - collect backscattered light from the target sectors in response to the steered optical beams,

- a photodetector arranged to receive the backscattered light from the beam steering device, and configured to interferometrically compare the backscattered light with the optical beam and to generate an interferometric signal therefrom;
- an acquisition and processing means configured to receive the interferometric signal, to form axial profiles of the target region therefrom and to merge said axial profiles to form a cross-section image of the patient’s body tissue.

[0023] The body tissue can be, for instance, the tissue of a wall of a body lumen such as a a hollow organ of a human or animal body or a blood vessel, in which case an IV-OCT apparatus is provided. In the latter case, the apparatus is also configured to carry out a translation movement along an axis of the lumen, e.g. a pullback translation m movement along inside the lumen, and the acquisition and processing means are configured to merge a plurality of cross section images to form a 3D image of a portion of interest of the patient body lumen.

[0024] In one aspect of the invention,

- the optical cable comprises a bundle of optical guide elements having a bundle axis;
- the beam steering device comprises:
  - a phase shifter device configured

    - to generate, at each moment of said radial scan time, a plurality of phase-shifted sample optical beams from the optical beam, the phase-shifted sample optical beams having respective phase shifts with respect to a reference phase of the optical beam, said phase shifts forming an instant combination of phase shifts, and
    - to modify said instant combination of phase shifts during said radial scan time, said instant combination of phase shifts arranged in such a way that an instant resulting beam is formed at the distal end of the cable as a combination of said phase-shifted sample optical beams, said instant resulting beam having a main intensity lobe oriented at an instant direction with respect to the bundle axis;
- a beam-deflection device fixedly arranged at the distal end, the beam-deflection device having a beam deflection surface arranged to:
    - at each time of said radial scan time, receive the corresponding instant resulting optical beam with its main intensity lobe at a respective position thereon; and
    - deflect the instant resulting optical beam at a respective beam rotation angle with respect to an angular reference position integral to the optical cable, so as to form, in said radial scan time, the steered optical beams;

such that the steered optical beams are directed towards the target sectors of the target region according to the beam rotation angles in said radial scan time, and the backscattered light is collected at the distal end in the form of backscattered optical beams backscattered from the

Ing. Marco Celestino
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Iscritto all'albo N. 544

respective target sectors in response to respective steered optical beams.

[0025] This way, an OCT apparatus is provided in which a high-speed mechanic-free optical beam steering (OBS) system is used to drive the radial scan, in other words the radial scan is performed without using moving components, which leads to some important advantages over the currently available optical coherence tomography systems, as described hereinafter.

[0026] Firstly, the scan rate can be speed up to values largely exceeding the upper scan speed limits of the known OCT systems, which use mechanically rotating parts such as rotating mirrors, or piezoelectric actuators. In particular, the radial scan rate can be increased by several orders of magnitude, and scan speed values of tens of MHz can be easily attained.

[0027] A more efficient imaging is therefore possible, in particular, in the case of rapidly evolving phenomena. For example, the high scan rate allows for new applications such as monitoring of coronary artery walls elasticity during heart beating, a crucial breakthrough for testing the correct positioning of a coronary stent following its application.

[0028] Secondly, no vibrations are associated to the operation of the optical beam steering proposed by the invention, which increases the available signal-to-noise ratio and improves therefore reliability and sensitivity up to performance levels impossible to reach with the known OCT systems.

[0029] Thirdly, faster scans limit the impact of the movements of the tissues, therefore leading to higher accuracy of the final image.

[0030] Fourthly, the optical beam steering device is simpler to manufacture and less likely to break down than conventional, mechanically operated beam steering devices, comprising very small moving parts. Therefore, maintenance and prospectively investment costs can be drastically reduced.

[0031] This way, the radial scan becomes the faster sweep among the wavelength sweep, the radial scan, and the pullback translation scan. Therefore, the 2D cross section rate is limited by the wavelength sweep rate rather than by the radial scan, leading to a record cross section rate.

[0032] In another aspect of the invention, the optical beam source is configured to emit a Gaussian optical beam, and an orbital angular momentum mode generator is provided configured to change the optical beam into a vortex light-mode optical beam having a helical wave front, such that the steered optical beams are also vortex light-mode steered optical beams, and the beam-deflection device is configured to deflect the vortex light-mode optical beams into the respective steered optical beams being vortex light-mode optical beams as well.

[0033] This way, by using vortex orbital angular momentum light modes, the maximum penetration depth of the OCT apparatus can be increased by up to 40% with respect to OCT system using conventional Gaussian beams. Axial penetration values up to 2.1 mm are therefore possible in an OCT apparatus according to the invention. This is particularly important in a SS-OCT system that, among other alternatives, offers the highest sensitivity, for IV applications.

[0034] As known, a light beam can propagate as a vortex, i.e. in such a way that its wave front is not a plane figure, as it is the case for a conventional Gaussian beam, but has the shape of a single or multiple helix. Wang, W.B. et al., Complex Light and Optical Forces X, 976410 (2016); Optics letters 41, no. 9 (2016), pages 2069-2072, as well as Cochenour et al., Applied optics 55, no. 31 (2016):C34-C38 disclose that light with a certain orbital angular momentum (OAM) is less prone to be scattered than gaussian beams, and that transmission of vortex beams in turbid media increases by increasing the order (L) of the OAM, which increases the maximum penetration depth. As shown by C. Brunet, and L.A. Rusch, Opt. Fibre Techn. 35, 2-7 (2017), modes carrying OAM can propagate as linear combinations of eigenmodes of the medium in multi-mode optical fibres (MMFs), which basically have a core promoting the separation between OAM modes and hence their stability during propagation.

[0035] The optical cable, and the possible optical guide elements contained in it, can be standard multi-mode optical fibres (MMF), which have been demonstrated to support OAM modes. In particular, modes carrying OAM can propagate along the multi-mode optical fibres as linear combinations of eigenmodes of the medium. As an alternative, more advanced specialty multi-mode optical fibres can be used such as vortex fibres with high-refractive-index ring, multi-OAM multi-ring fibre, photonic crystal fibre, supermode OAM fibre, air-core fibre, and inverse-parabolic graded-index fibre, which can support OAM modes for km-reach with remarkable stability. Basically, all these fibre designs include a core that promotes the separation between OAM modes and hence their stability during propagation. In particular, step-index MMF provides a lower degeneracy, showing a better isolation of modes families with the same values of orbital angular momentum.

[0036] As an alternative, the orbital angular momentum mode generator is provided configured to change the Gaussian optical beam into a vortex light-mode optical beam having a helical wave front, and the phase shifter device is configured to sequentially generate the plurality of phase-shifted sample optical beams as vortex light-mode phase-shifted sample optical beams from the vortex light-mode optical beam.

[0037] The combination of the features of the two aspects of the invention, i.e. the use of OAM light beams and of a high-speed mechanic-free optical beam steering (OBS) system leads to performance never attained by the prior art in connection with both scan rate, axial penetration depth and accuracy.

[0038] Preferably, the beam-deflection device comprises a conical mirror arranged at the distal end coaxially to the bundle of optical guide elements, the conical mirror having a vertex angle whose amplitude is selected according to the angle α between the direction of the instant resulting beam and the bundle axis. Preferably, the amplitude of the vertex angle is determined by the relationship:

$$\gamma = \alpha/2+ \pi/4.$$

This way, the instant resulting beam hits the conical mirror on a plurality of points forming a circular trajectory, which is travelled along with a period equal to said radial scan time. Accordingly, the backscattered optical beams follow the same optical paths as the respective steered optical beams in response to which the backscattered optical beams are emitted at the target sectors, in the opposite direction from the target sectors to the distal end.

[0039] In particular, the phase shifter device comprises:

- an optical power splitter device configured for splitting the optical beam into a plurality of replicas thereof;
- an optical phase shifter array comprising a plurality of optical phase shifters, i.e. phase modulators, each arranged to receive a respective replica of the replicas, and configured to change the replica into a phase-shifted optical beam of the phase-shifted optical beams.

[0040] Advantageously, the phase shifter device comprises a photonic integrated circuit comprising integrated doped light guide elements as the optical phase shifters, the doped light guide elements configured to receive a voltage so as to modify a refractive index thereof. This way, the reliability of the apparatus is strengthened thanks to the excellent optical phase stability guaranteed by the photonic integration.

[0041] Preferably, a coupler device is provided arranged to direct the phase-shifted optical beams into predetermined respective optical guide elements of the bundle, the coupler device is selected from the group comprised of:

- a plurality of grating couplers connecting with an efficient mode coupling the optical beam steering device with each of the optical guide elements;
- a plurality of edge emitters with a taper profile, so as to implement an efficient mode coupling from each phase-shifted sample optical beam provided by the optical beam steering device, and the mode supported by each of the optical guide elements.

[0042] Advantageously, the integrated light guide elements are implemented as fast doped p-n junctions. This way, in addition to the benefits due to the absence of mechanical vibrations, the scan speed can be improved by several orders of magnitude. In particular, the p-n junction can work under reverse bias. In this case, the solution exhibits a potential speed up to the GHz range.

[0043] However, the coupler device can comprise an ad-hoc photonic torque of any type, provided it is configured to opportunely convert the mode propagated into the integrated waveguide to the mode supported by the optical guide elements.

[0044] As an alternative, each of said optical phase shifters can comprise a doped optical guide portion of a respective optical guide element, the doped optical guide portion configured to receive a voltage so as to modify a refractive index thereof. In other words, an optical phased array is included in the catheter end, whose emitters are the ends of the bundle guide elements. In this case, in order to avoid moving parts to accomplish the radial scan, the apparatus includes an optical beam steering functionality based on an optical phased array.

[0045] As known, a phased array is an array of antennas electronically scanned in phase in such a way to create a RF beam that can be electronically steered in different directions without moving the antennas. Optical phased arrays have been also developed in the last decades for such applications as optical sensing and high-power lasers. The use of integrated waveguide grating couplers and a 2-D array of liquid crystal phase shifting elements greatly reduced the phase shifter spacing. More recently, sophisticated CMOS compatible nanotechnology solutions offered a very high number of emitters with high spatial density. However, for such applications such as IVOCT, where a sub-mm thick probe needs to deliver/collect light till/from the catheter end along blood vessels for ~2 meters, it might be more convenient to exploit fibres or fibre bundles as emitters of the phased array.

[0046] In a preferred embodiment, the diagnostic apparatus is an SS-OCT apparatus, i.e. one in which the optical beam source is a continuous-wave wavelength-sweeping source.

[0047] The typical tuning speed of a CW-SS is in the range 20-50 KHz, while the tuning speed of a typical rotating mirror is hundreds of Hertz. Therefore, conventional moving mirror-based IV-OCT solutions exhibit radial scan rates in the range of hundreds of Hertz. On the contrary, in the present invention the radial scan rate can reach values as high as 10 to 25 MHz, which can be obtained if phase shifters are doped p-n junction-based. This way, similarly to most commercial apparatus, the system will collect hundreds of axial lines per cross section, but at such a rate that, unlike the conventional apparatus, is imposed by the CW-SS sweeping rate rather than by the radial scan rate, therefore a radial scan rate in the order of tens of KHz can be reached.

[0048] Advantageously, the optical cable comprises a fibre having a refractive index profile configured to guide optical angular momentum modes. To this purpose, in particular, the fibre is selected from the group comprised of:

- multi-OAM multi-ring fibre;
- photonic crystal fibre;
- supermode OAM fibre;
- air-core fibre;
- inverse-parabolic graded-index fibre.

Brief description of the drawings

[0049] The invention will be now shown with the following description of its exemplary embodiments, exemplifying but not limitative, with reference to the attached drawings in which:

- Figs. 1A and 1B diagrammatically shows a conventional IV-OCT apparatus;
- Fig. 1C is a flow diagram showing how data are processed in a conventional IV-OCT apparatus to yield a 3D OCT image of a portion of interest of a blood vessel;
- Fig. 2A is a block diagram of an IV-OCT apparatus according to one aspect of the invention, in which a high-speed mechanic-free OBS system is used to drive the radial scan, in which a beam steering device includes a phase shifter device and a beam-deflection device;
- Fig. 2B is a diagrammatical cross section view of a beam deflection device of the apparatus of Fig. 2A and of a patient’s lumen within which the beam deflection device is positioned.
- Fig. 2C is a block diagram showing how data are processed in the IV-OCT apparatus of Figs. 2A and 2B to obtain an OCT image of a portion of interest of a blood vessel;
- Fig. 2D is a flow diagram of an acquisition and processing means of the apparatus of Fig. 2A;
- Fig. 3A is a block diagram of an IV-OCT apparatus according to another aspect of the invention, in which an orbital angular momentum mode generator is provided to change an optical beam into a vortex light-mode optical beam;
- Fig. 3B is a diagrammatical cross section view of a beam deflection device of the apparatus of Fig. 3A and of a patient’s lumen within which the beam deflection device is positioned.

- Fig. 4A is a block diagram of an IV-OCT apparatus, including features of both aspects of Figs. 2 and 3, in which the orbital angular momentum mode generator is arranged downstream of the phase shifter device to treat a plurality of gaussian phase-shifted optical beam;
- Figs 4B illustrates features of the apparatus of Fig. 4A corresponding to features shown by Fig. 2B, for the apparatus of Fig. 2.
- Fig. 5A is a block diagram of an IV-OCT apparatus including features of both aspects of Figs. 2 and 3, in which the orbital angular momentum mode generator is arranged upstream of the phase shifter device to treat a gaussian optical beam emitted by an optical beam source;
- Figs 5B illustrates features of the apparatus of Fig. 5A corresponding to features shown by Fig. 2B, respectively, for the apparatus of Fig. 2.
- Fig. 6A is a block diagram of an IV-OCT apparatus including the features of the apparatus of Fig. 2, in which the beam-deflection device comprises a conical mirror;
- Figs 6B illustrate features of the apparatus of Fig. 6A corresponding to features shown by Fig. 2B, respectively, for the apparatus of Fig. 2A.
- Fig. 7A is a block diagram of an IV-OCT apparatus having the features of the apparatus of Fig. 2, in which the phase shifter device comprises i.a. an optical phase shifter array, in which the phase shifter device is implemented by a photonic integrated circuit used to control the beam steering;
- Figs 7B illustrate features of the apparatus of Fig. 7A corresponding to features shown by Fig. 2B, respectively, for the apparatus of Fig. 2A;

- Fig. 8A is a block diagram of an IV-OCT apparatus having the features of the apparatus of Fig. 2, in which the phase shifter device comprises i.a. an optical phase shifter array, in which the phase shifter device also comprises a plurality of grating couplers each including a terminal micro-lens for collimating respective phase-shifted optical beams;
- Figs 8B illustrates features of the apparatus of Fig. 8A corresponding to features shown by Figs. 2B, respectively, for the apparatus of Fig. 2A;
- Fig. 9A is a block diagram of an embodiment of apparatus like in Fig. 8A, also including an orbital angular momentum mode generator.
- Figs 9B illustrates features of the apparatus of Fig. 8A corresponding to features shown by Fig. 2B, respectively, for the apparatus of Fig. 2A.

Detailed description of the invention

[0050] Optical coherence tomography (OCT) apparatuses 102 and 103 are described with reference to Figs. 2A to 3B, according to distinct aspects of the invention.

[0051] OCT apparatuses 102 and 103 includes an optical beam source 10 configured to emit a main optical beam 11. A splitter device 21 is preferably provided to split main optical beam 11 into a sample optical beam 12 and a reference optical beam 18, to be used for OCT signal coherent detection, as described hereinafter.

[0052] In the description, reference will be made to apparatuses that are configured to perform a 3D-scan of a portion 8 of a patient's body lumen 1, i.e. to carry out a 3D scan of a wall of body lumen 1. In particular, the apparatuses are suitable for intra-vascular applications (IV-OCT). However, the invention is not limited to an IV-

OCT application and can be used to build tomographic images of a patient's body tissue in general.

[0053] To this purpose, apparatuses 102 and 103 comprises an optical cable 40, associated to an optical catheter that is configured to travel from a vascular entry site and through an intravascular path, not shown, until a distal end 49 of optical cable 40 reaches a target region 2_l of patient's body lumen 1. An optical probe 60 is arranged at distal end 49, and is optically connected to optical source 10 to deliver light 14_j derived from main optical beam 11, e.g. from sample optical beam 12, to target region 2_l.

[0054] Like prior art devices diagrammatically shown in Figs. 1A-B, optical beam source 10 of apparatuses 102 and 103 is configured to conventionally perform a light wavelength sweep 9λ, in order to obtain a given axial resolution of the wall of body lumen 1 when delivering light 14j to target region 2_l.

[0055] Moreover, in order to carry out the wall scan, apparatuses 102 and 103 are also configured to cause optical probe 60 to perform a radial 360° scan (B-scan) 9β of the wall of patient's body lumen 1 at target region 2_l in a predetermined radial scan time T, to allow for a 2D visualization at target region 2_l. To this purpose, optical probe 60 includes a beam-deflection device 70,70' arranged at distal end 49 of optical cable 40, so that it can receive light 13_j,13' from optical cable 40. Beam-deflection device 70,70' is configured to sequentially deflect received light 13_j,13' into steered optical beams 14_1, 14_2,…14_j,…14_M at respective moments t_j of radial scan time T ($t_M = T$). Steered optical beams 14_j are oriented at predetermined respective beam rotation angles β_1, β_2,…β_j,… β_M with respect to an angular reference position β_0 integral to optical cable 40. Therefore, during radial scan

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Iscritto all'albo N. 544

time T, optical beams 14_j are sent through beam-deflection device 70,70′ to respective target sectors $2_{j,l}$ of target region 2_l angularly spaced apart by beam rotation angles β_j from a reference position corresponding to said angular reference position β_0.

[0056] Moreover, apparatuses 102 and 103 are also configured to conventionally perform a usually concomitant pullback translation 9z of probe 60 along body lumen 1, in order to generate a 3D volumetric data set.

[0057] Beam-deflection device 70,70′ of optical probe 60 is also configured to collect backscattered optical beams 16_1, 16_2,…16_j,…16_M reflected back from target sectors $2_{1,l}$, $2_{2,l}$,…$2_{j,l}$,…$2_{M,l}$, respectively, when the latter are hit by steered optical beam 14_j, and to deflect backscattered optical beams 16_j back through distal end 49 and optical cable 40 to proximal end 41, as deflected backscattered optical beams 17_j or directly into a deflected backscattered light optical beam 17 in the apparatuses 102,103, respectively, as described hereinafter.

[0058] OCT apparatuses 102 and 103 also include a balanced photodetector 29 that is arranged to receive backscattered light optical beam 17, and to interferometrically compare the latter with main optical beam 11 or, in particular, with reference optical beam 18. Moreover, photodetector 29 is configured to generate an interferometric signal 19 from this comparison. An acquisition and processing means 90 is configured to receive interferometric signal 19 from balanced photodetector 29, and to reconstruct cross-section images 98_l, $l=1…S$ of target region 2_l and, starting therefrom, 3D image 99 of portion of interest 8.

[0059] As shown in Fig 2C, image acquisition and processing means 90 preferably comprises an amplifier 92 configured to low-noise amplify interferometric signal 19, an analogue-to-digital converter (ADC) 93 configured to convert possibly amplified, analogue interferometric signal 19′ into a digital signal 19″, and a buffer 94 in which digital signal 19″ is stored as an acquisition matrix $A_{k,j}$, where k,j are the wavelength index and the angle index, respectively. Each column of matrix $A_{k,j}$ represents the wavelength interferogram 95 in the probed wavelength range for a respective radial angle, i.e. at a respective target sectors $2_{j,l}$ of target region 2_l.

[0060] More in detail, Image acquisition and processing means 90 includes an FFT computation means 96 configured to Fourier-transform inteferogram 95, into the axial line $97_{j,l}$ for a given orientation angle β_j of steered optical beam 14.

[0061] Acquisition and processing means 90 is also configured to collect consecutive axial lines $97_{j,l}$ j=1…M for the whole 360° radial scan, and to reconstruct the 2D cross section 98_l and, through a pull-back motion of optical probe 60, the 3D image 99 of the artery 1 by merging together consecutive cross sections 98_l, l=1…S for instance, by a helicoidal interpolation procedure.

[0062] With reference to Figs. 2A and 2B, in a first aspect of the invention, OCT apparatus 102 comprises a high-speed mechanic-free optical beam steering system to perform the radial scan of target region 2_l by deflecting light 13_j received from optical cable 40 into steered optical beams 14_j at respective moments t_j of radial scan time T, in such a way to direct steered optical beams 14_j to target sectors $2_{j,l}$ angularly spaced apart from one another by relative beam rotation angles $\beta_j-\beta_{j-1}$.

[0063] To this purpose, according to the first aspect of the invention, optical cable 40 comprises a bundle 43 of optical guide elements 42_i e.g. optical fibres 42_i.

Ing. Marco Celestino
ABM Agenzia Brevetti & Marchi
Iscritto all'albo N. 544

[0064] Moreover, according to the first aspect of the invention, a phase shifter device 20 is provided to generate one plurality of N phase-shifted sample optical beams $12_{i,j}$, i=1…N, from sample optical beam 12 at each moment t_j of radial scan time T. Each of the N phase-shifted sample optical beams $12_{i,j}$ has a phase shift $\theta_{i,j}$ with respect to a reference phase θ_0 of sample optical beam 12. Phase shifter device 20 and optical cable 40 are mutually arranged in such a way that each phase-shifted sample optical beam $12_{i,j}$ can be directed into a predetermined respective optical fibre 42_i of bundle 43.

[0065] More in detail, phase shifter device 20 is configured to phase-shift sample optical beam 12 in multiple ways. In other words, at each moment t_j, j=1…M, of radial scan time T, a plurality of N phase-shifted sample optical beams $12_{i,j}$, i=1…N are generated having a given instant combination $\underline{\boldsymbol{\theta}}_j$ of phase shifts $\theta_{i,j}$. Therefore, at each moment t_j, at distal end 49 of bundle 43 a number N of phase-shifted sample optical beams 12_i are contemporaneously released with interference, thus forming an instant resulting optical beam 13_j that has a radiation diagram with a main intensity lobe oriented at an instant direction with respect to an axis 44 of bundle 43, the instant direction depending therefore on the instant combination $\underline{\boldsymbol{\theta}}_j$ of phase shifts $\theta_{i,j}$. At a subsequent moment t_{j+1}, a subsequent instant resulting optical beam 13_{j+1} is formed from a plurality of N of phase-shifted sample optical beams $12_{i,j+1,}$ having a different instant combination $\underline{\boldsymbol{\theta}}_{j+1}$ of phase shifts $\theta_{i,j+1}v$, and so on for each j value during radial scan time T.

[0066] Moreover, still according to the first aspect of the invention, the beam-deflection device is a motionless beam-deflection device 70, i.e. it is fixedly arranged in optical probe 60 at distal end 49, preferably coaxially to bundle 43, and has a beam deflection surface arranged to receive the corresponding instant resulting optical beam 13_j from distal end 49 of cable 40, and to deflect by reflection instant resulting optical beam 13_j into respective steered optical beam 14_j at predetermined respective beam rotation angles β_j with respect to angular reference position β_0 integral to bundle 43, as shown in Fig. 2B.

[0067] Therefore, in radial scan time T, steered optical beams 14_j are sent by beam-deflection device 70 towards respective target sectors $2_{j,1}$ of target region 2_1. In substantially the same radial scan time T, backscattered optical beams 16_j are deflected back by the deflection surface of motionless beam-deflection device 70, thus forming deflected backscattered optical beams 17_j that are directed back to phase shifter device 20 via respective optical fibres 47_i, i= 1…n

[0068] Briefly, at distal end 49 of optical cable 40, by properly and dynamically shifting optical phase $\theta_{i,j}$ of various interfering output phase-shifted sample optical beams $12_{i,j}$ (Figs. 2A,6A,7A,8A) or $12'_{i,j}$ (Fig.4A,5A,9A) with respect to each other, it is possible to obtain steering and shaping capabilities of the instant resulting optical beams 13_j so as to implement a continuous beam deflection with a specific deflection angle (e.g 100 mrad) and a circular trajectory 55.

[0069] Moreover, phase shifter device 20 is also configured to mix backscattered optical beams 17_j into backscattered light optical beam 17.

[0070] More in detail, back-reflected light beams 16_j are deflected back by beam-deflection device 70 into back-reflected beams 17_j, and then are collected by part of fibres 47_i included in fibre bundle 43, whose number and geometrical layout are preferably defined selected through numerical analysis, during the probe design activity.

[0071] With reference to Fig. 2C, by the apparatus according to the invention, matrix $A_{k,j}$ is "filled" row-by-row, i.e. during each wavelength step k, k=1…R, a complete 360° radial scan is performed. Therefore, if T_λ is the time at which optical beam source 10 is set to perform a light wavelength sweep Λ, this is also the time required to fill matrix $A_{k,j}$, which is required to obtain cross-section image 98_l of target region 2 of portion of interest 8 (Fig. 1).

[0072] On the contrary, in the conventional technique, a wavelength sweep is carried out during time T_λ for each angular position 2_{j-1} before investigating a subsequent angular position 2_j, j=1…M and therefore, with same optical beam source 10 as before, a time $M \times T_\lambda$ is required to acquire matrix $A_{k,j}$ in order to obtain cross-section image 98_l of target region 2.

[0073] Therefore, in the invention, the process of reconstructing each cross-section image 98_l is far faster than in the prior art methods. For example, in a conventional SS-OCT apparatus that collects M=500 axial profiles per each 360° radial scan, through a 25 MHz-rate angular scan, easily achieved through optical phase shifters, the time required to acquire matrix $A_{k,j}$ would be 500 times shorter. As a consequence, considering a commercial 50 KHz-rate swept source and a 100 Hz-rate mechanically rotating mirror, a cross section acquisition time of 10 ms could be decreased down to 200 µs through the use of optical phase shifting-based radial scan according to the invention.

[0074] With reference to Figs. 3A and 3B, in a second aspect of the invention, OCT apparatus 103 advantageously uses vortex light-mode optical beams to enhance axial penetration depth capability of the optical coherence tomography (OCT) apparatus.

[0075] According to a second aspect of the invention, in OCT apparatus 103 optical beam source 10 is configured to emit a gaussian main optical beam 11, and an orbital angular momentum mode (OAM) generator 30 is provided configured to change gaussian sample optical beam 12 derived therefrom into a vortex light-mode sample optical beam 12′.

[0076] A beam-deflection device 70′ is arranged at an end of optical probe 60 to deflect vortex light-mode sample optical beam 12′,13' into vortex light-mode steered optical beams 14_j at respective moments t_j of radial scan time T, i.e. into a diverted turning vortex light-mode optical beam 14_j directed towards target sectors $2_{j,l}$. Beam deflection device 70′ can be a conventional deflection device as currently in use in OCT techniques, such as a mirror rotatably arranged at a rotation speed ω about an own rotation axis 71, or another deflection device of known type, e.g. MEMS, galvomirrors or piezoelectric actuators.

[0077] In some embodiments featuring both aspects of the invention, beam-deflection device 70′ can be a beam deflection device 70 as mentioned above in connection with Figs. 2A and 2B. Such embodiments will be described more in detail hereinafter, with reference to Figs. 4A-5B, 9A and 9B.

[0078] In substantially the same radial scan time T, backscattered optical beams 16_j are deflected back by beam-deflection device 70′, thus forming backscattered light optical beam 17 directed to photodetector 29 via optical cable 40.

[0079] Figs. 4A and 4B relate to an OCT apparatus 104 according to an embodiment of the invention, in which features of both first aspect (Figs. 2A and 2B) and second aspect (Figs. 3A-3B) of the invention are provided. In comparison with OCT apparatus 102 of Fig. 2A, OCT apparatus 104 includes an OAM generator 30 arranged downstream of phase shifter device 20. OAM generator 30 is configured to turn, phase-shifted sample optical beams $12_{i,j}$ into vortex light-mode phase-shifted sample optical beams $12'_{i,j}$, i=1…N, at each moment t_j, i=1…M, of radial scan time T. Therefore, beam-deflection device 70 will steer vortex light-mode phase-shifted sample optical beams $13'_{i,j}$ into respective steered vortex light-mode optical beams $14'_j$, and target sectors $2_{j,l}$ of target region 2_l will be irradiated by respective vortex light-mode optical beams.

[0080] Figs. 5A and 5B relate to an OCT apparatus 105 according to another embodiment of the invention that includes features of both first aspect (Figs 2A and 2B) and second aspect (Figs. 3A-3B) of the invention. In OCT apparatus 105, OAM generator 30 is arranged upstream of phase shifter device 20. Like in OCT apparatus 103 (Fig. 3A), OAM generator apparatus 30 is configured to change gaussian sample optical beam 12 derived from main optical beam 11 emitted by beam source 10 into vortex light-mode sample optical beam 12'. In this case, phase shifter device 20 is configured to sequentially generate the plurality of vortex light-mode phase-shifted sample optical beams $12'_{i,j}$ from vortex light-mode sample optical beam 12'. Therefore, also in this case beam-deflection device 70 will steer vortex light-mode phase-shifted sample optical beams $13'_{i,j}$ into respective steered vortex light-mode optical beams $14'_j$, and target sectors $2_{j,l}$ of target region 2_l will be irradiated by respective vortex light-mode optical beams.

[0081] In the case of apparatuses 103, 104 and 105 of Figs. 3A, 4A and 5A, optical cable 40 or fibres 42_i and 47_i thereof, respectively, are configured to support OAM propagation, for instance they can be standard multi-mode optical fibres (MMF) or even more advanced specialty MMF such as vortex fibres with high-refractive-index ring, multi-OAM multi-ring fibre, photonic crystal fibre, supermode OAM fibre, air-core fibre, and inverse-parabolic graded-index fibre.

[0082] With reference to Figs. 6A and 6B, in a diagnostic OCT apparatus 106 according to the first aspect of the invention, beam-deflection device is a conical mirror 70 arranged at distal end 49 of optical cable 40. Conical mirror 70 is preferably arranged coaxially to bundle 43, in other words the axis 72 of conical mirror 70 substantially coincides with longitudinal axis 44 of bundle 43.

[0083] This way, instant resulting optical beams 13_j, j=1…M released by optical cable 40 at distal end 49 at different moments t_j of radial scan time T hit conical mirror 70 in different points of a circular trajectory 55, i.e. a section of conical mirror 70 obtained by a plan perpendicular to axis 72 of conical mirror 70. Therefore, at each moment $t_1, t_2,…t_j,…t_M$, instant resulting optical beams $13_1,13_2,…13_j,…13_M$ are deflected radially, i.e. perpendicularly to axis 72, so as to form respective radially deflected beams $14_1,14_2,…14_j,…14_M$ oriented at predetermined respective beam rotation angles $\beta_1,\beta_2,…\ \beta_j,…\ \beta_M$ with respect to angular reference position $\beta 0$, describing a 360° angle about axis 72. This way, radial 360° scan (B-scan) of target region 2_l of patient’s body lumen 1 is performed, in which target sectors $2_{1,l},2_{2,l},…2_{j,l},…2_{M,l}$ are sequentially irradiated.

Ing. Marco Celestino
ABM Agenzia Brevetti & Marchi
Iscritto all’albo N. 544

[0084] Preferably, conical mirror 70 has a vertex angle whose amplitude γ is selected according to the angle α between the direction of instant resulting beam 13_j and bundle axis 44. In particular, amplitude γ is selected according to the relationship:

$$\gamma = \alpha/2 + \pi/4.$$

[0085] Static mirrors different from conical mirror 70 can be used as well, in particular conical mirrors having an axisymmetric surface, provided they are arranged to change instant resulting beams 13_j into radially deflected beams 14_j.

[0086] With reference to Fig. 7A, an OCT apparatus 107 according to the first aspect of the invention is described, in which phase shifter device 20, including an optical phase shifter array 23, is implemented by a photonic integrated circuit configured to control the beam steering process.

[0087] Downstream of first optical power splitter device 21, which can be included in integrated circuit 20, phase shifter device 20 also includes a second optical power splitter device 22, configured for splitting sample optical beam 12 into a plurality of N replicas 12_i thereof, i=1…N.

Optical phase shifter array 23 comprises a plurality of optical phase shifters 23_i, i=1…N, i.e. phase modulators that are optically coupled with respective optical fibres 47_i of bundle 43 by a coupler device 24. At a given moment t_j of radial scan time T, each optical phase shifter 23_i is configured for changing a replica 12_i into a respective phase-shifted sample optical beams $12_{i,j}$. Therefore, each optical fibre 42_i is arranged for guiding a respective sample optical beams $12_{i,j}$ received from respective optical power splitter element 22_i. In particular, integrated phase shifters 23_i are implemented as fast doped p-n junctions that CAN work under reverse bias, with the advantages explained above.

[0088] Back-reflected light 17_j can travel back to photonic integrated circuit 20 input through a dual path, with respect to their previous transmission. Optical phase $\theta_{i,j}$ of each received signal is controlled again by phase shifters 27_j, to be initially calibrated with a reference target, i.e. a mirror, before being coupled together.

[0089] OCT apparatus 108 of Figs. 8A and 8B is a modification of OCT apparatus 107, in which coupler device 24 of phase shifter device 20 advantageously comprises a plurality of grating couplers 24_i connecting each output of phase-shifter array 23 with a respective optical fibre 42_i of bundle 43. Each grating coupler 24_i advantageously includes a terminal micro-lens 25_i for collimating respective sample optical beams $12_{i,j}$ into each of optical fibres 42_i.

[0090] As an alternative, in order to properly connect each output of phase-shifter array 23 with a respective optical fibre 42_i, coupler device 24 can consist of suitable mode tapers to convert the mode propagated into the integrated waveguide to the mode supported by the optical fibres 42_i. As a further alternative, any type of ad-hoc photonic torque can be used that is designed to opportunely convert the mode propagated into the integrated waveguide to the mode supported by the optical fibres 42_i. The same applies also for backscattered light 17j to be conveyed from fibres 47i into input of phase-shifter array 27.

[0091] An OCT apparatus 109, shown in Figs. 9A and 9B, is a modification of OCT apparatus 108 of Figs. 8A and 8B also including the features of the second aspect of the invention, i.e. an angular momentum mode generator 30 \arranged downstream of the phase shifter device 20 as in

Fig. 4A. Each micro-lens 25_i is optically connected with orbital angular momentum mode generator 30 configured to turn each phase-shifted sample optical beams $12_{i,j}$ into a respective OAM-mode- carrying phase-shifted sample optical beams $12'_{i,j}$, having a helical wave front.

[0092] Grating couplers 24_i and possibly respective micro-lens 25_i are optically connected with respective fibres 42_i of fibre bundle 43 of optical cable 40 through proper bulk optics, so that each phase-shifted sample optical beams $12_{i,j}$ (Fig. 8) or the OAM mode-carrying phase-shifted sample optical beams $12'_{i,j}$ (Fig. 9) becomes coupled into a core of respective fibre 42_i.

[0093] Fibre bundle 43 is configured to convey sample optical beams $12_{i,j}$ or $12'_{i,j}$ to an end of optical probe 60 and to collect a backscattered light 16_j, consisting of a plurality of backscattered beams 16_j coming from respective target sectors $2_{j,l}$ of target region 2_l under test, in this case, a portion of a patient's blood vessel 1.

[0094] Due to the encumbrance of the employed bulk optics, fibre bundle 43 will be of the fan-out type as shown throughout the set of pictures, i.e. fibres 42_i are spaced-apart thin-cladding fibres at proximal end 41 of optical cable i.e. cable 40, and are progressively gathered into a closest packed structure towards distal end 49 of optical cable 40, so as to limit the thickness thereof to less than 1 mm.

[0095] Still with reference to Fig. 9A, OCT apparatus 109, as well as any other previously-described OCT apparatus 101-108, can be an SS-OCT apparatus in which continuous-wave swept-source (CW-SS) 10 is provided configured to linearly sweep the wavelength range Λ of emitted main optical beam 1 in a predetermined wavelength scan time T_λ that may range between 20 µs and 50 µs.

[0096] Moreover, optical beam source 10 is optically connected, preferably through fibre pig-tailing, to photonic integrated circuit 20, which has preferably the form of a silicon-on-insulator integrated circuit, in order to direct main optical beam 11 to integrated circuit 20.

[0097] In some embodiments, not shown, the angle β_M within which the radial scan is performed may be different from a 360° angle, if required. The size of each target sector $2_{j,l}$ depends on the number N of phase shifters, i.e. of the elements of the optical phased array implementing the OBS, on mutual distance between fibres 42i at distal end 49, on their geometry, distribution, and on further parameters that are obvious for a person skilled in the art of optical phased array and the art to which the invention pertains.

[0098] The foregoing description exemplary specific embodiments will so fully reveal the invention according to the conceptual point of view, so that others, by applying current knowledge, will be able to modify and/or adapt for various applications such embodiment without further research and without parting from the invention and, accordingly, it is therefore to be understood that such adaptations and modifications will have to be considered as equivalent to the specific embodiment exemplified. The means and the materials to realise the different functions described herein could have a different nature without, for this reason, departing from the field of the invention. It is to be understood that the phraseology or terminology that is employed herein is for the purpose of description and not of limitation.

RIVENDICAZIONI - CLAIMS

1. A diagnostic apparatus (102,104,105,106,107,108,109) for performing an optical coherence tomography of a target region (2_l) of a patient's body tissue (1), said diagnostic apparatus comprising:

- an optical beam source (10) configured to emit an optical beam (11);
- an optical cable (40) having a proximal end (41) in communication with said optical beam source (10) to receive said optical beam (11) therefrom, and a distal end (49) arranged to be introduced into said target region (2_l);
- a beam steering device configured to:
  - steer said optical beam (11) at a plurality of beam rotation angles (β_j) with respect to an angular reference position (β_0) integral to said optical cable (40), in a predetermined radial scan time (T), so as to obtain a plurality of respective steered optical beams (14_j), and to direct said steered optical beams (14_j) sequentially in said radial scan time (T) towards a plurality of respective target sectors ($2_{j,l}$) of said target region (2_l);
  - collect backscattered light (17) backscattered from said target sectors ($2_{j,l}$) in response to said steered optical beams (14_j),
- a photodetector (29) arranged to receive said backscattered light (17) from said beam steering device, and configured to interferometrically compare said backscattered light (17) with said optical beam (11,18) and to generate an interferometric signal (19) therefrom;

- an acquisition and processing means (90) configured to receive said interferometric signal (19), to form axial profiles ($97_{j,l}$) of said target region (2_l) therefrom, and to merge said axial profiles ($97_{j,l}$) to form a cross-section image (98_l) of said patient's body tissue (1),

characterised in that:

- said optical cable (40) comprises a bundle (43) of optical guide elements (42_i), said bundle (43) having a bundle axis (44);
- said beam steering device comprises:
  - a phase shifter device (20) configured
    - to generate, at each moment of said radial scan time, a plurality of phase-shifted sample optical beams ($12_{i,j}$) from said optical beam (11), said phase-shifted sample optical beams ($12_{i,j}$) having respective phase shifts ($\theta_{i,j}$) with respect to a reference phase (θ_0) of said optical beam (11), said phase shifts ($\theta_{i,j}$) forming an instant combination ($\underline{\boldsymbol{\theta}}_j$) of phase shifts, and
    - to modify said instant combination ($\underline{\boldsymbol{\theta}}_j$) of phase shifts during said radial scan time (T), said instant combination ($\underline{\boldsymbol{\theta}}_j$) of phase shifts arranged in such a way that an instant resulting optical beam (13_j) is formed at said distal end (49) of said cable (40) as a combination of said phase-shifted sample optical beams ($12_{i,j}$), said instant resulting optical beam (13_j) having a main intensity lobe oriented at an instant direction with respect to said bundle axis (44);

- a beam-deflection device (70) fixedly arranged at said distal end (49), said beam-deflection device (70) having a beam deflection surface arranged to:
  - at each moment of said radial scan time (T), receive the corresponding instant resulting optical beam (13_j) at a respective position thereon; and
  - deflect said instant resulting optical beam (13_j) at a respective beam rotation angle (β_j) of said rotation angles about said optical cable (40), so as to form, in said radial scan time (T), said steered optical beams (14_j);

such that said steered optical beams (14_j) are directed towards said target sectors ($2_{j,l}$) of said target region (2_l) according to said beam rotation angles (β_j) in said radial scan time (T), and said backscattered light (17) is collected at said distal end (49) in the form of backscattered optical beams (16_j) backscattered from respective said target sectors ($2_{j,l}$) in response to respective said steered optical beams (14_j).

2. The diagnostic apparatus (104,109) according to claim 1, wherein said optical beam source (10) is configured to emit a gaussian optical beam (11), and an orbital angular momentum mode generator (30) is provided configured to change each of said phase-shifted sample optical beams ($12_{i,j}$) into vortex light-mode phase-shifted sample optical beams ($12'_{i,j}$) having helical wave fronts, and said beam-deflection device (70) is configured to deflect said vortex light-mode phase-shifted sample optical beams ($12'_{i,j}$) into said steered optical beams (14_j), said steered optical beams being vortex light-mode optical beams (14_j).

3. The diagnostic apparatus (105) according to claim 1, wherein said optical beam source (10) is configured to emit a gaussian optical beam (11), and an orbital angular momentum mode generator (30) is provided configured to change said gaussian optical beam (11) into a vortex light-mode optical beam (12’) having a helical wave front, and said phase shifter device (20) is configured to sequentially generate said plurality of phase-shifted sample optical beams as vortex light-mode phase-shifted sample optical beams ($12'_{i,j}$) from said vortex light-mode optical beam (12’).

4. A diagnostic apparatus (103,104,105,109) for performing an optical coherence tomography of a target region (2_l) of a patient’s body tissue (1), said diagnostic apparatus comprising:

- an optical beam source (10) configured to emit an optical beam (11);
- an optical cable (40) having a proximal end (41) in communication with said optical beam source (10) to receive said optical beam (11) therefrom, and a distal end (49) arranged to be introduced into said target region (2_l);
- a beam steering device configured to:
  - steer said optical beam (11) at a plurality of beam rotation angles (β_j) with respect to an angular reference position (β_0) integral to said optical cable (40), in a predetermined radial scan time (T), so as to obtain a plurality of respective steered optical beams (14_j), and to direct said steered optical beams (14_j) sequentially in said radial scan time (T)

towards a plurality of respective target sectors ($2_{j,l}$) of said target region (2_l);

  - collect backscattered light (17) backscattered from said target sectors ($2_{j,l}$) in response to said steered optical beams (14_j),

- a photodetector (29) arranged to receive said backscattered light (17) from said beam steering device, and configured to interferometrically compare said backscattered light (17) with said optical beam (11) and to generate an interferometric signal (19) therefrom;
- an image acquisition and processing means (90) configured to receive said interferometric signal (19) and to form axial profiles of said target region (2_l) therefrom, and to merge said axial profiles ($97_{j,l}$) to form a cross-section image (98_l) of said patient's body tissue (1),

characterised in that

said optical beam source (10) is configured to emit a gaussian optical beam, and an orbital angular momentum mode generator (30) is provided configured to change said optical beam (11) into a vortex light-mode optical beam (12') having a helical wave front, such that said steered optical beams (14_j) are also vortex light-mode steered optical beams and said beam steering device is configured to sequentially generate said plurality of phase-shifted sample optical beams ($12_{i,j}$) from said vortex light-mode optical beam (12').

5. The diagnostic apparatus (104,105,109) according to claim 4, wherein:

- said optical cable (40) comprises a bundle (43) of optical guide elements (42_i), said bundle (43) having a bundle axis (44);

- said beam steering device comprises:
    - a phase shifter device (20) configured
        - to generate, at each moment (t_j) of said radial scan time (T), a plurality of phase-shifted sample optical beams ($12_{i,j}$) from said optical beam (11), said phase-shifted sample optical beams ($12_{i,j}$) having respective phase shifts ($\theta_{i,j}$) with respect to a reference phase (θ_0) of said optical beam (11), said phase shifts ($\theta_{i,j}$) forming an instant combination ($\underline{\boldsymbol{\theta}}_j$) of phase shifts, and
        - to modify said instant combination ($\underline{\boldsymbol{\theta}}_j$) of phase shifts during said radial scan time (T), said instant combination ($\underline{\boldsymbol{\theta}}_j$) of phase shifts arranged in such a way that an instant resulting optical beam (13_j) is formed at said distal end (49) of said cable (40) as a combination of said phase-shifted sample optical beams ($12_{i,j}$), said instant resulting optical beam (13_j) having a main intensity lobe oriented at an instant direction with respect to said bundle axis (44);
    - a beam-deflection device (70) fixedly arranged at said distal end (49), said beam-deflection device (70) having a beam deflection surface arranged to:
        - at each time of said radial scan time (T), receive the corresponding instant resulting optical beam (13_j) at a respective position thereon; and
        - deflect said instant resulting optical beam (13_j) at a respective beam rotation angles

(β_j) of said rotation angles about said optical cable (40), so as to form, in said radial scan time (T), said steered optical beams (14_j);

such that said steered optical beams (14_j) are directed towards said target sectors ($2_{j,l}$) of said target region (2_l) according to said beam rotation angles (β_j) in said radial scan time (T), and said backscattered light (17) is collected at said distal end (49) in the form of backscattered optical beams (16_j) backscattered from respective said target sectors ($2_{j,l}$) in response to respective said steered optical beams (14_j).

6. The diagnostic apparatus (106,109) according to claims 1 or 5, wherein said beam-deflection device comprises a conical mirror (70) arranged at said distal end (49) coaxially to the bundle (43) of optical guide elements (42_i), said conical mirror (70) having a vertex angle whose amplitude (γ) is selected according to the angle (α) between the direction of said instant resulting optical beam (13_j) and the bundle axis (44), in particular, by the relationship:

$$\gamma = \alpha/2 + \pi/4,$$

where γ is the amplitude of said vertex angle of said conical mirror (70), and α is the angle between the direction of said instant resulting optical beam (13_j) and the bundle axis (44).

7. The diagnostic apparatus (107,108,109) according to claims 1 or 5, wherein said phase shifter device (20) comprises:

- an optical power splitter device (22) configured for splitting said optical beam (11) into a plurality of replicas (11_i) thereof;

— an optical phase shifter array (23) comprising a plurality of optical phase shifters (23_i), i.e. phase modulators, each arranged to receive a respective replica (11_i) of said replicas, and configured to change said replica (11_i) into a phase-shifted optical beam (12_i) of said phase-shifted optical beams (12_i);

— a coupler device (24) arranged to direct said phase-shifted optical beams (12_i) into predetermined respective optical guide elements (42_i) of said bundle (43).

8. The diagnostic apparatus (108,109) according to claim 7, wherein said phase shifter device (20) comprises a photonic integrated circuit (20) comprising integrated doped light guide elements (23_i) as said optical phase shifters, said doped light guide elements (23_i) configured to receive a voltage so as to modify a refractive index thereof,

wherein said coupler device (24) is selected from the group comprised of:

— a plurality of grating couplers (24_i) connecting said optical beam steering device (20) with each of said optical guide elements (42_i);

— a plurality of edge emitters with a taper profile,

in particular, said integrated light guide elements (23_i) comprise fast doped p-n junctions, more in particular, said doped p-n junctions are arranged to work under reverse bias.

in particular, each of said optical phase shifters (23_i) comprises a doped optical guide portion of a respective of said optical guide elements, said doped optical guide portion configured to receive a voltage so as to modify a refractive index thereof.

Ing. Marco Celestino
ABM Agenzia Brevetti & Marchi
Iscritto all'albo N. 544

9. The diagnostic apparatus (109) according to claim 1 or 4, wherein said optical beam source (10) is a continuous-wave wavelength-sweeping source.

10. The diagnostic apparatus according to claims 2 or 3 or 4, wherein said optical cable (40) comprises a fibre selected from the group comprised of:

- a multi-OAM multi-ring fibre;
- a photonic crystal fibre;
- a supermode OAM fibre;
- an air-core fibre;
- an inverse-parabolic graded-index fibre.

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RIASSUNTO - ABSTRACT

An optical coherence tomography apparatus (109) comprises an optical beam source (10), an optical cable (40) with a proximal end (41) to receive an optical beam (11) therefrom and a distal end (49) to be introduced into a patient's target region (2_l), as well as a beam steering device configured to change the optical beam (11), during a radial scan time (T), into a plurality of respective steered optical beams (14_j) sequentially directed towards a plurality of respective target sectors ($2_{j,l}$) of the target region (2_l) at a plurality of beam rotation angles (β_j), and to collect backscattered light (17) from the target sectors ($2_{j,l}$) in response to the steered optical beams (14_j). The apparatus conventionally also comprises a photodetector (29) and an acquisition and processing means (90) to form axial profiles ($97_{j,l}$) of the target region (2_l) from an interferometric signal (19), and to merge them into a cross-section image (98_l) of the target region. In a first aspect of the invention, the optical cable (40) is a bundle (43) of optical guide elements (42_i) and the beam steering device comprises a phase shifter (20) configured to generate from the optical beam (11), at each moment of the radial scan time (T), a plurality of phase-shifted sample optical beams ($12_{i,j}$) having respective phase shifts ($\theta_{i,j}$) forming an instant phase shifts combination ($\underline{\boldsymbol{\theta}}_j$), and to modify the latter during the radial scan time (T) forming an instant resulting optical beam (13_j) at the distal end (49) of the cable (40) including the phase-shifted sample optical beams ($12_{i,j}$) and having a main intensity lobe oriented at an instant direction with respect to the bundle axis (44); the beam steering device also comprises a fixed beam-deflection device (70) at the distal end (49), with a preferably conical deflection surface to receive corresponding instant resulting optical beams (13_j) at respective points thereon at respective moments of the radial scan time (T), and to deflect them into the steered optical beams (14_j) at respective beam rotation angles (β_j). In another aspect, an orbital angular momentum mode generator (30) is configured to change the optical beam (11) into a vortex light-mode optical beam (12'), such that the steered optical beams (14_j) are vortex light-mode steered optical beams as well. (Fig. 4)

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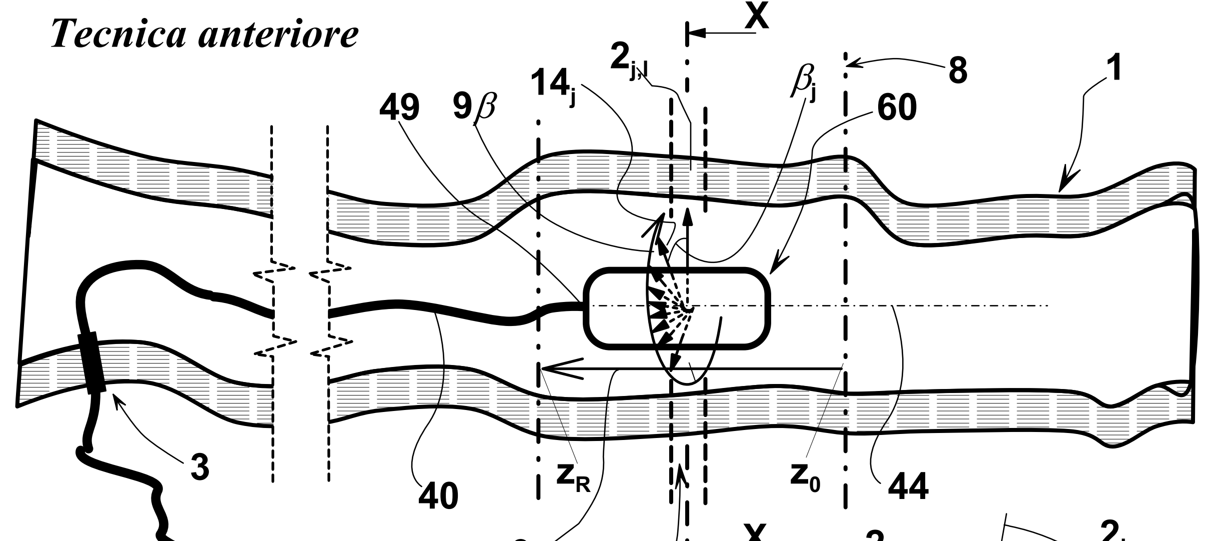
Fig. 1A

Tecnica anteriore



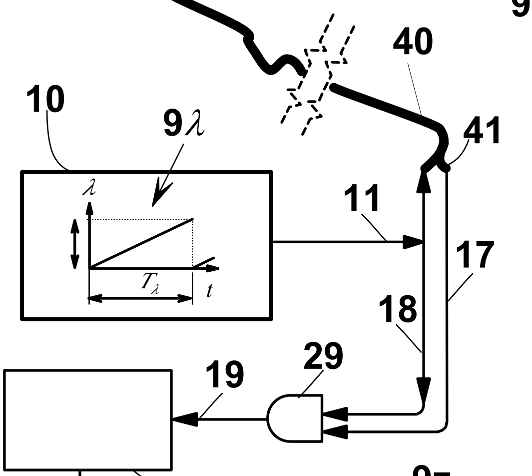


Fig. 1B

X-X

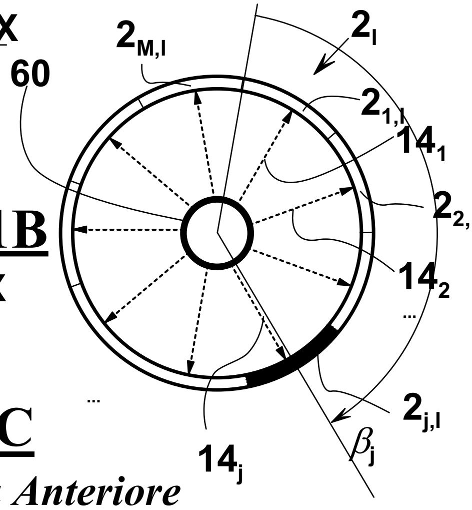
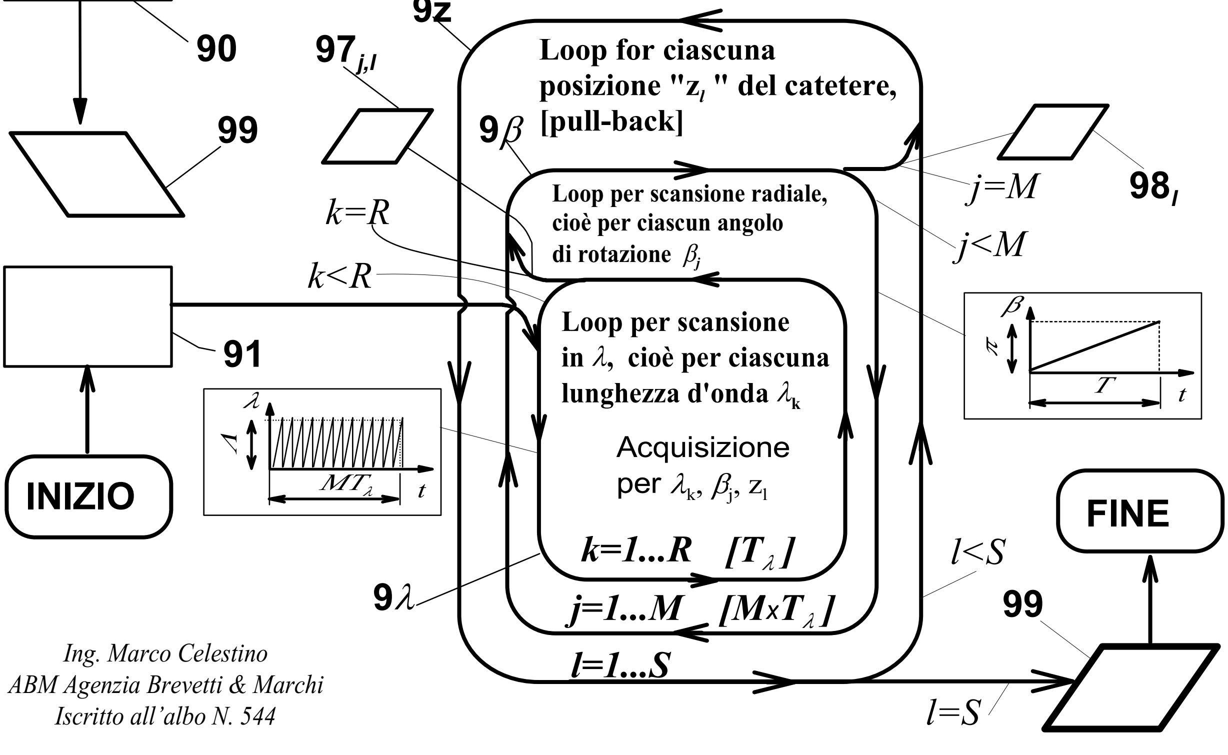


Fig. 1C

Tecnica Anteriore



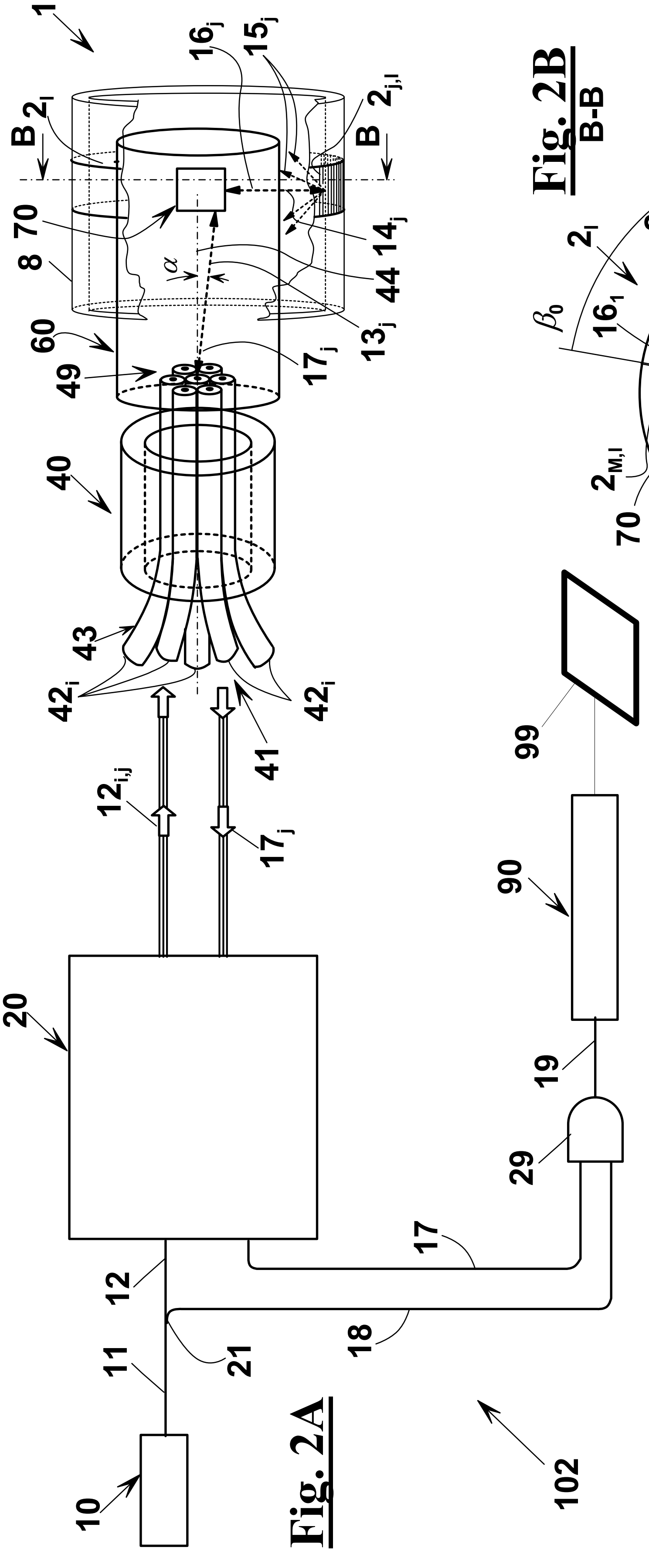


Fig. 2A

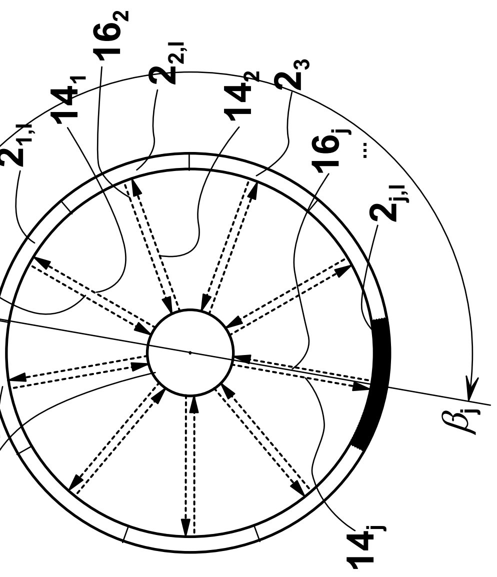


Fig. 2B
B-B

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Fig. 2C

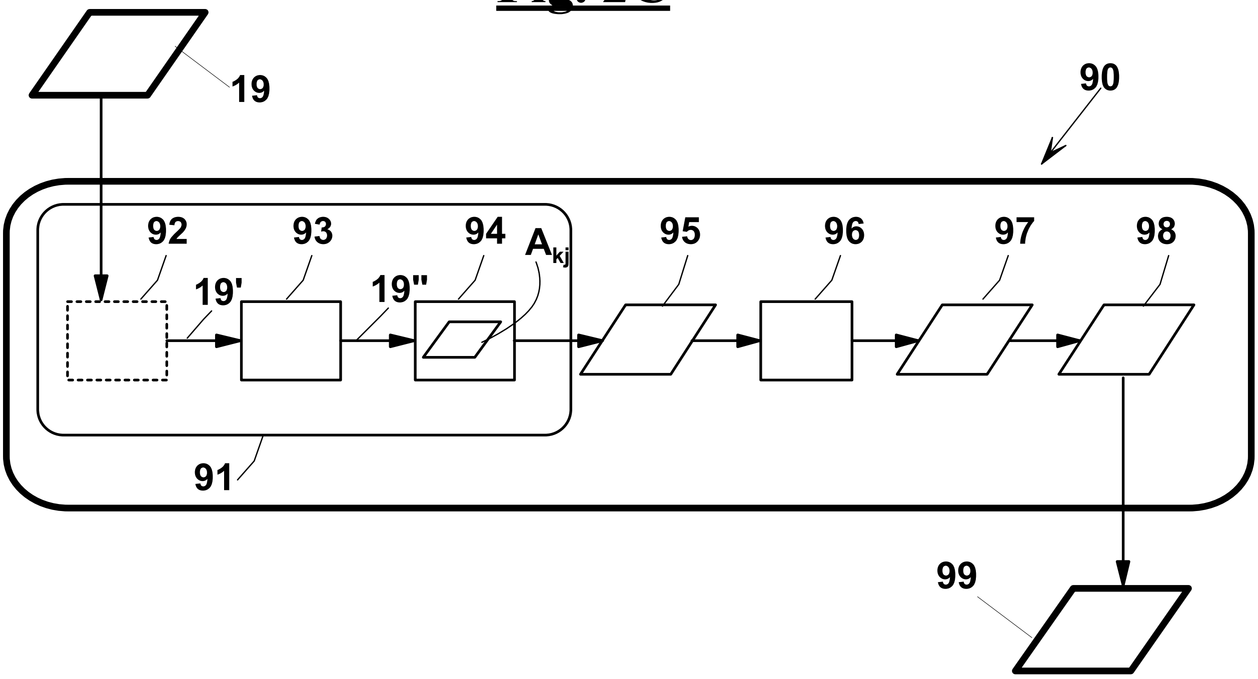
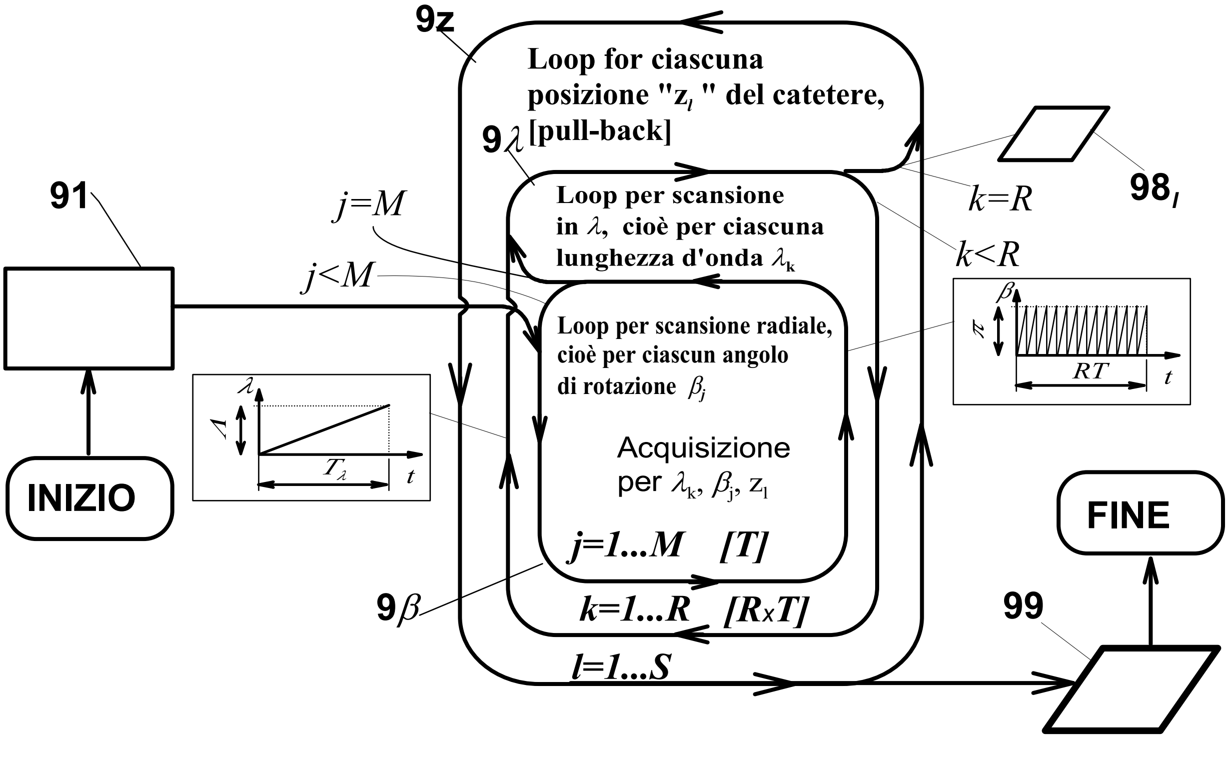

19
90
92
93
94
A_{kj}
95
96
97
98
19'
19"
91
99

Fig. 2D


9z
Loop for ciascuna posizione "z_l" del catetere, [pull-back]
9λ
Loop per scansione in λ, cioè per ciascuna lunghezza d'onda λ_k
98$_l$
k=R
k<R
91
j=M
j<M
Loop per scansione radiale, cioè per ciascun angolo di rotazione β_j
Acquisizione per λ_k, β_j, z_l
j=1...M [T]
k=1...R [RxT]
l=1...S
9β
β
π
RT
t
λ
Λ
T_λ
t
INIZIO
FINE
99

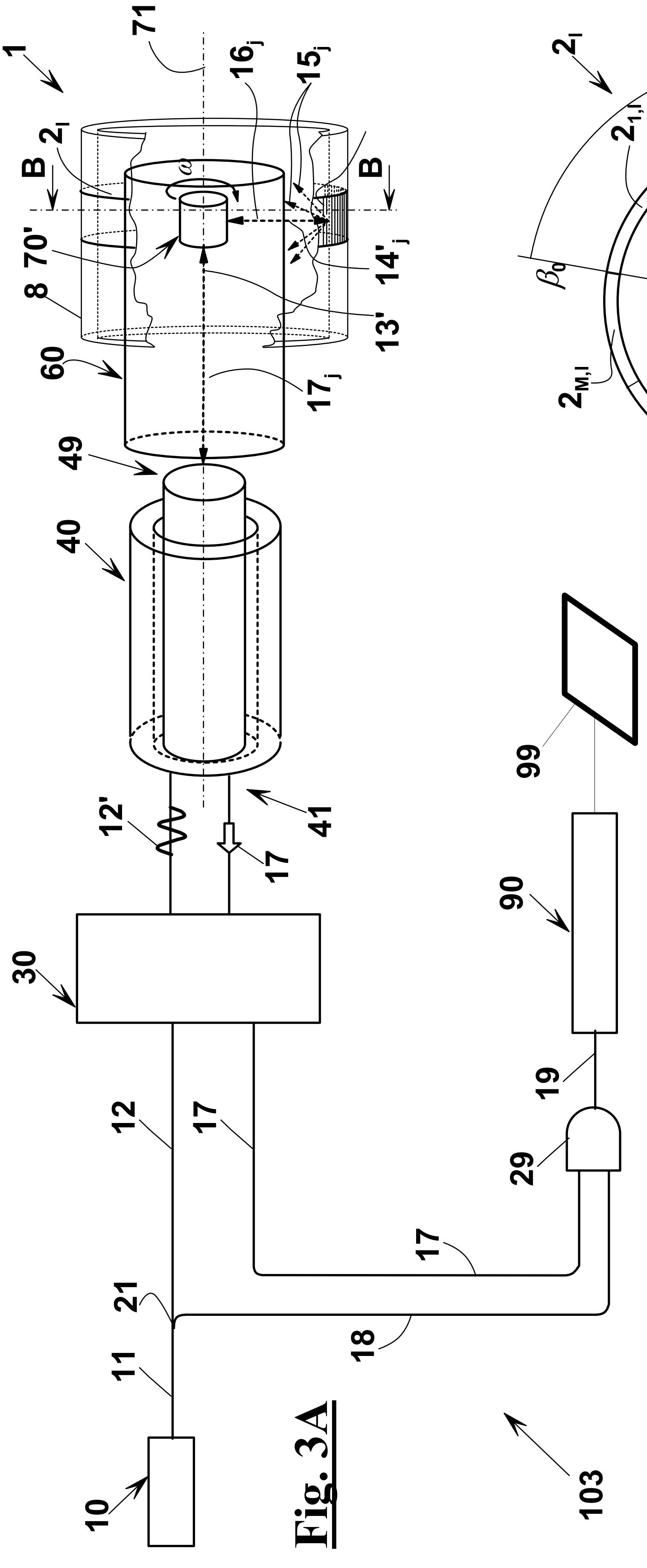


Fig. 3A

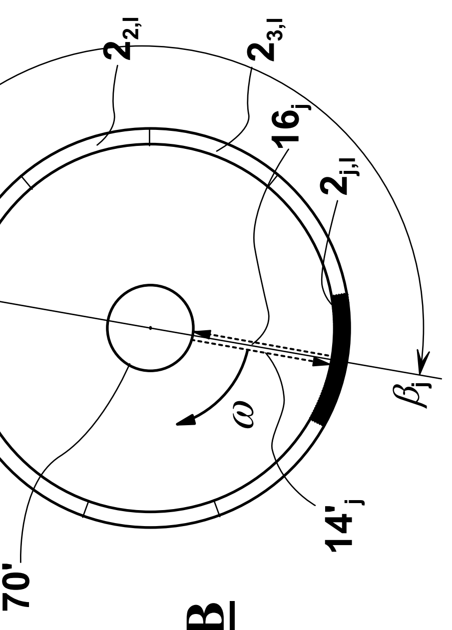


Fig. 3B
B-B

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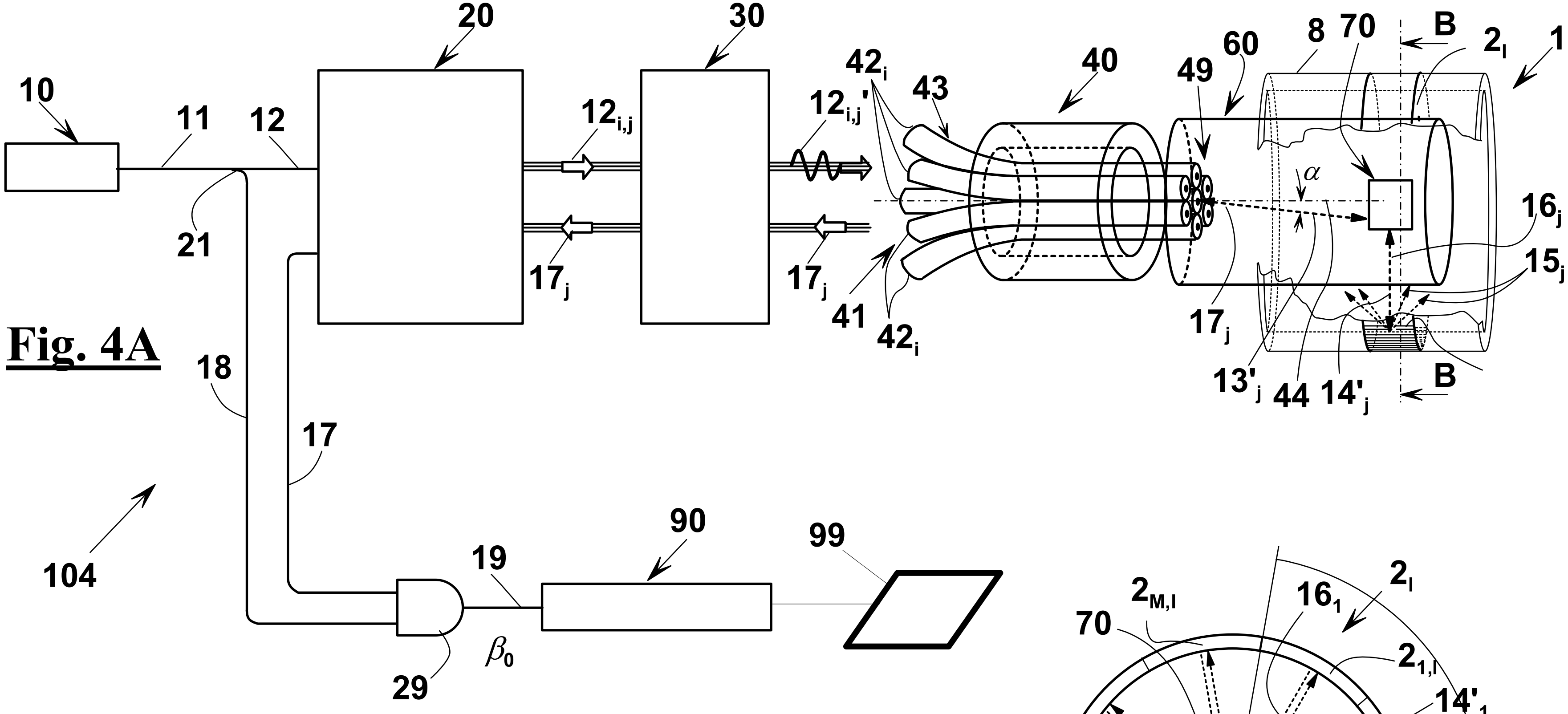

Fig. 4A

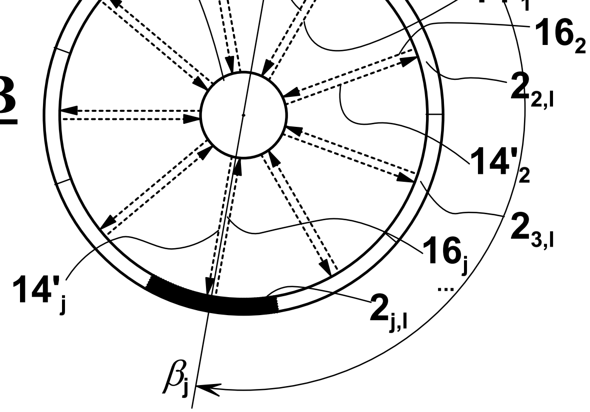

Fig. 4B
B-B

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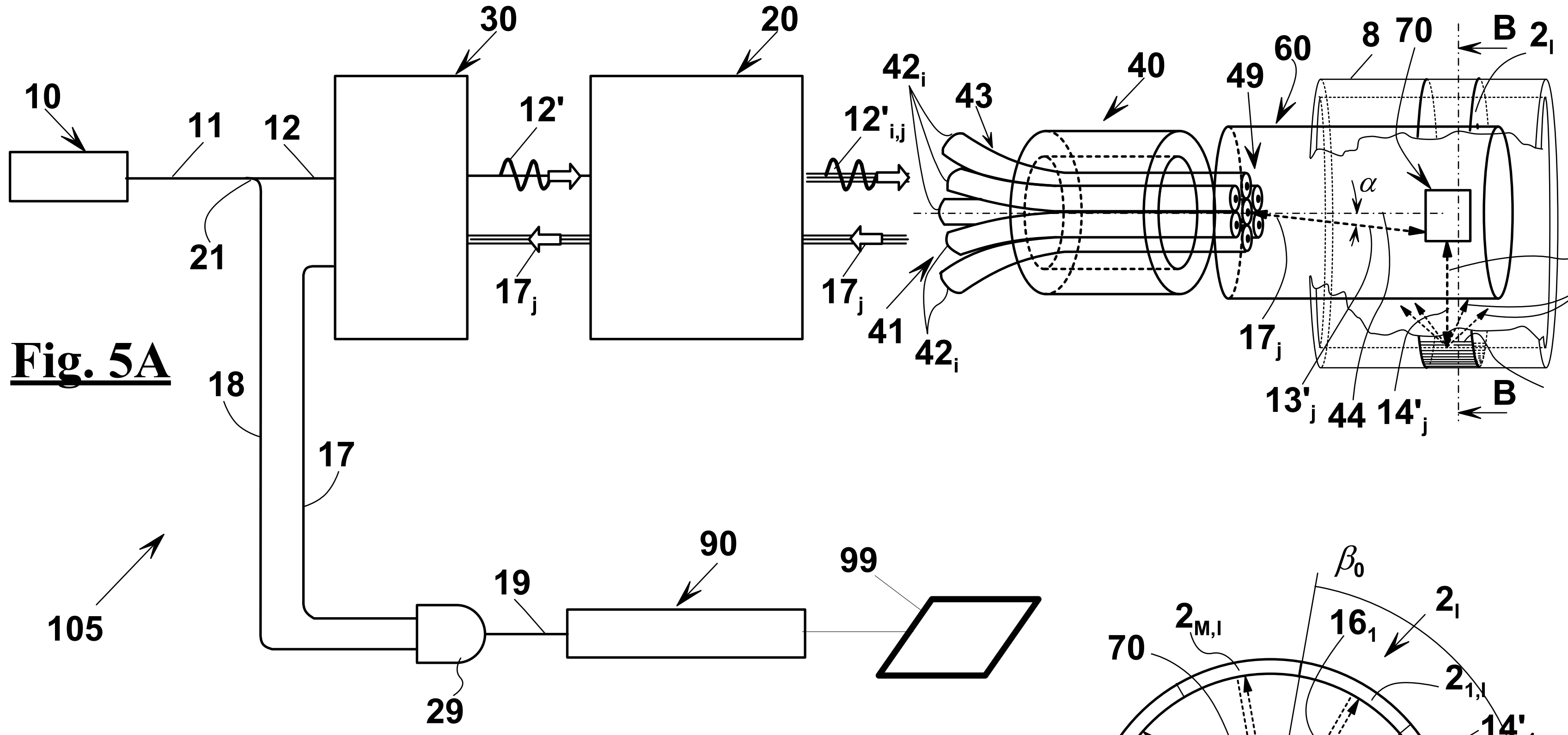

Fig. 5A

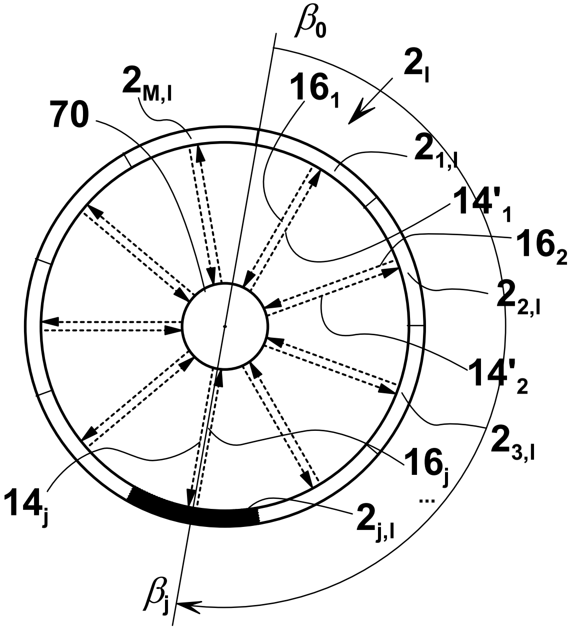

Fig. 5B
B-B

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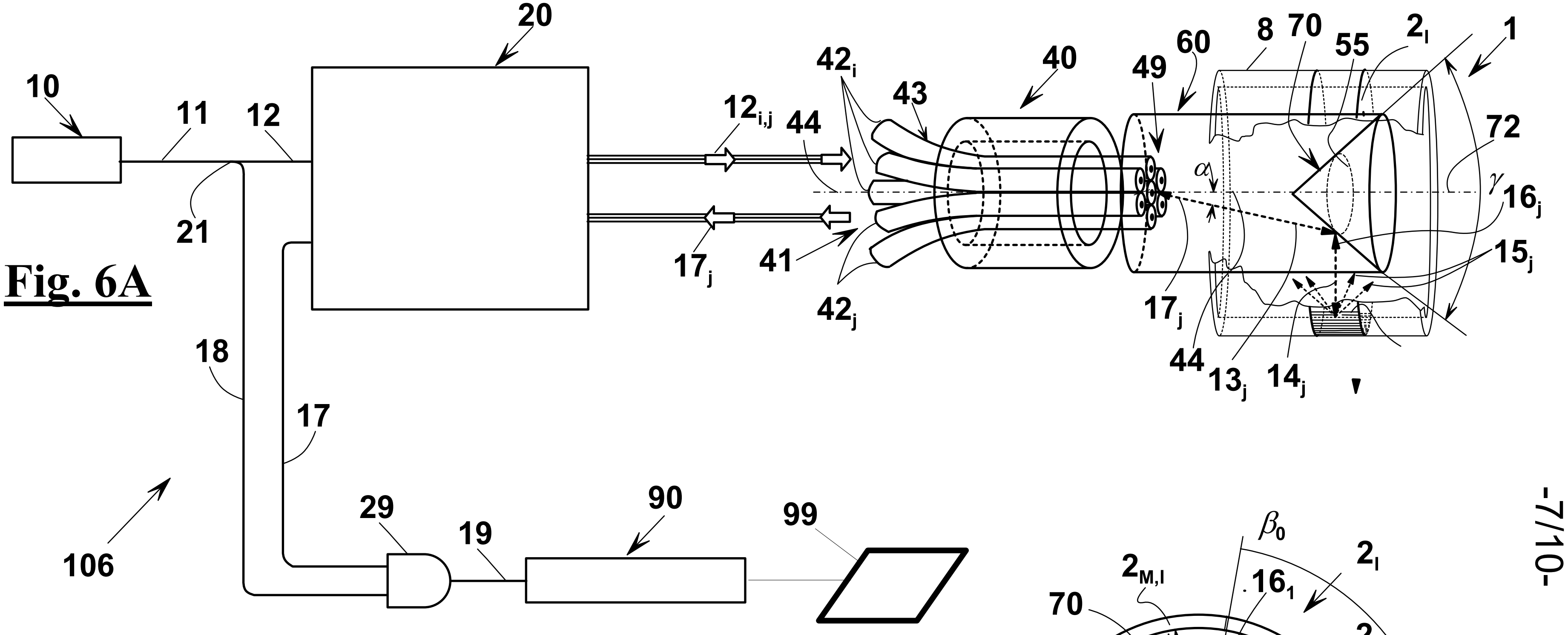

Fig. 6A

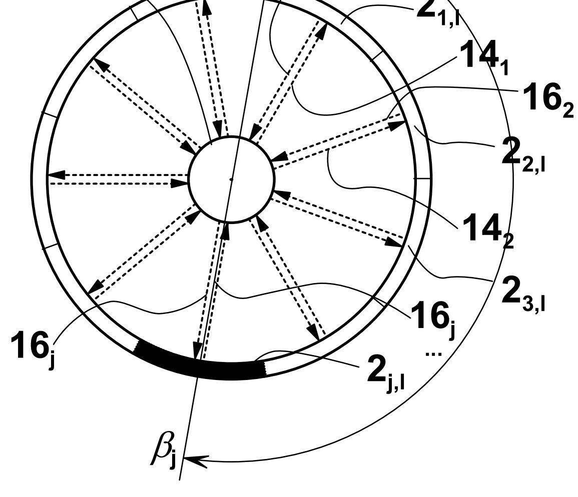

Fig. 6B
B-B

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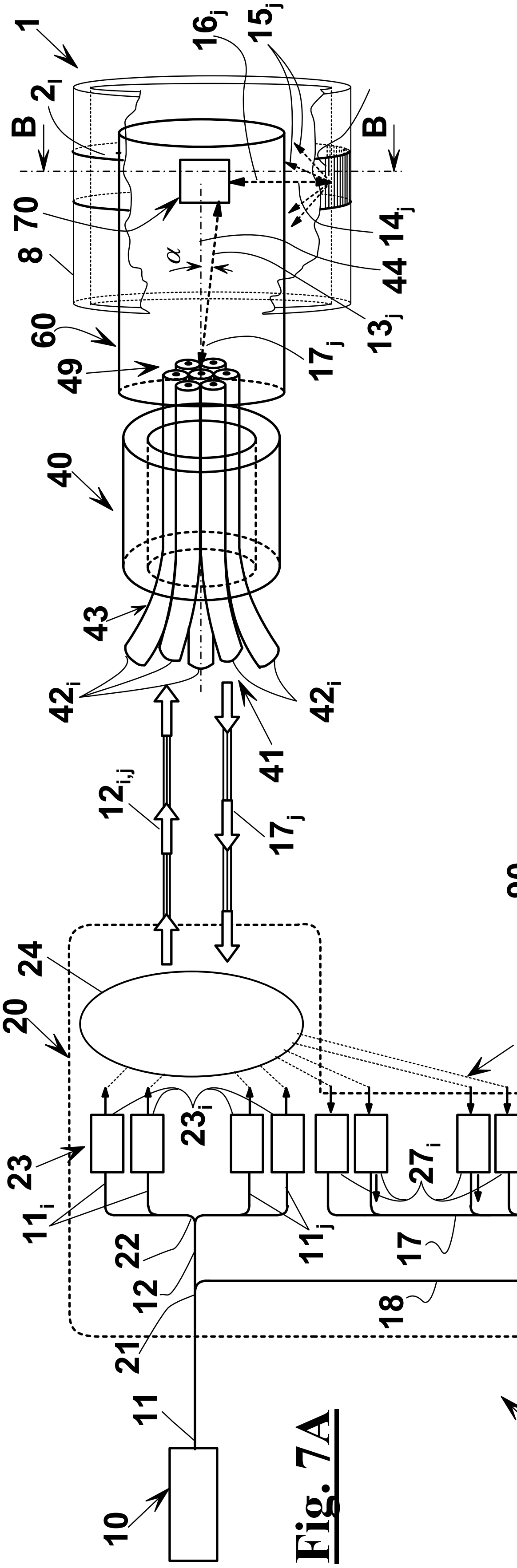

Fig. 7A

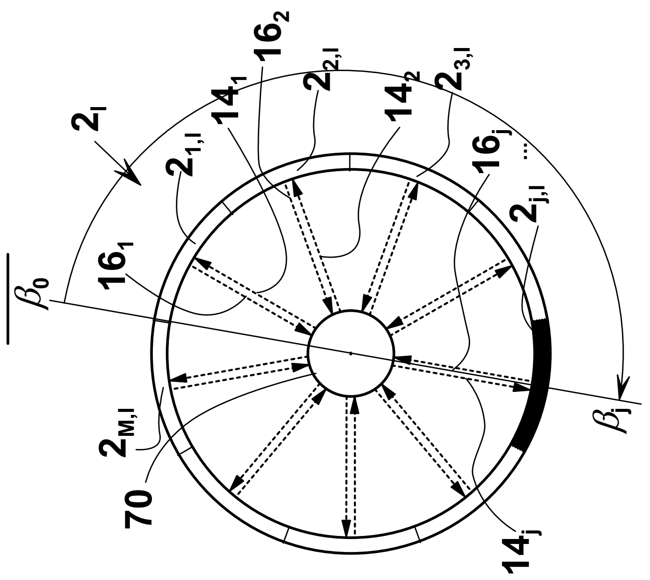

Fig. 7B
B-B

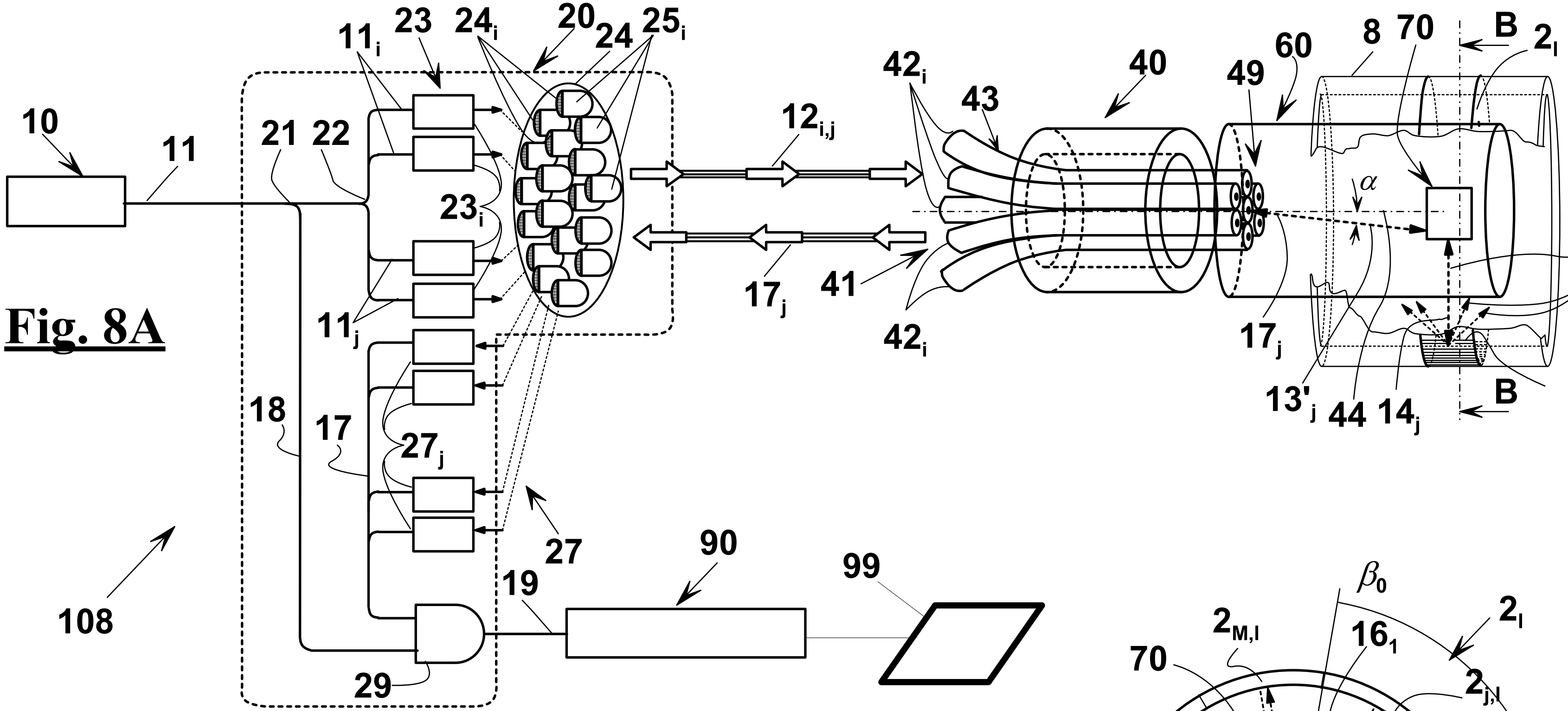

Fig. 8A

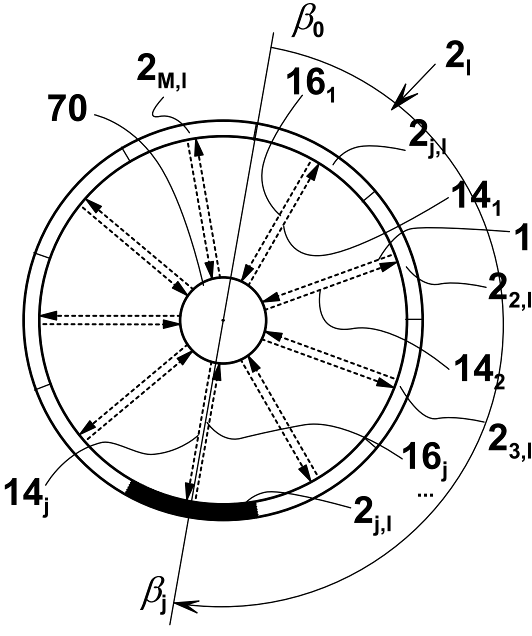

Fig. 8B
B-B

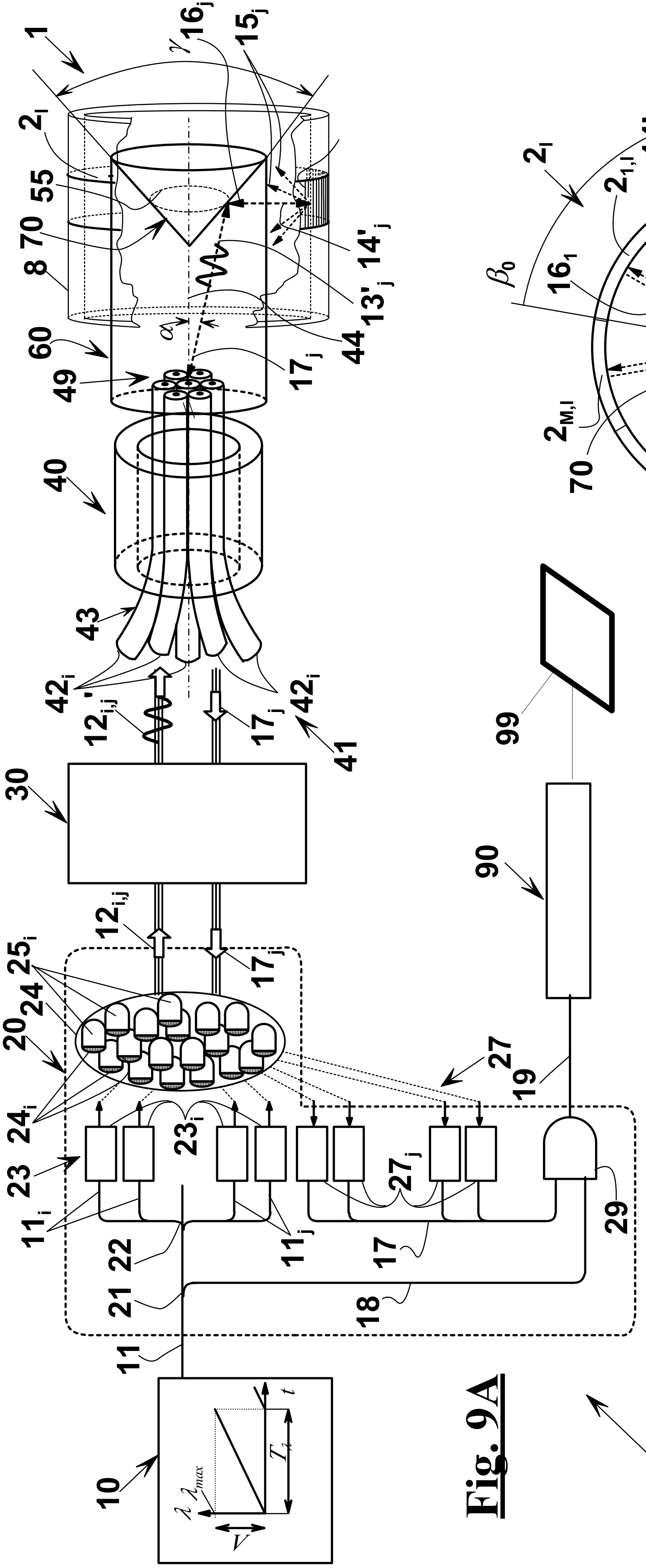

Fig. 9A

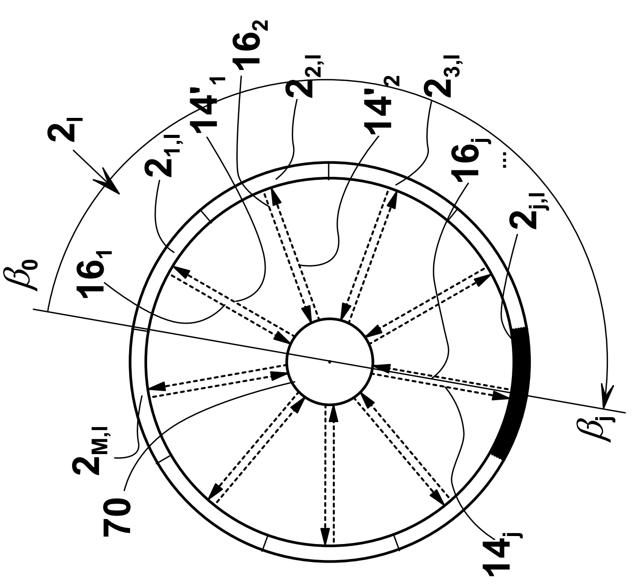

Fig. 9B
B-B

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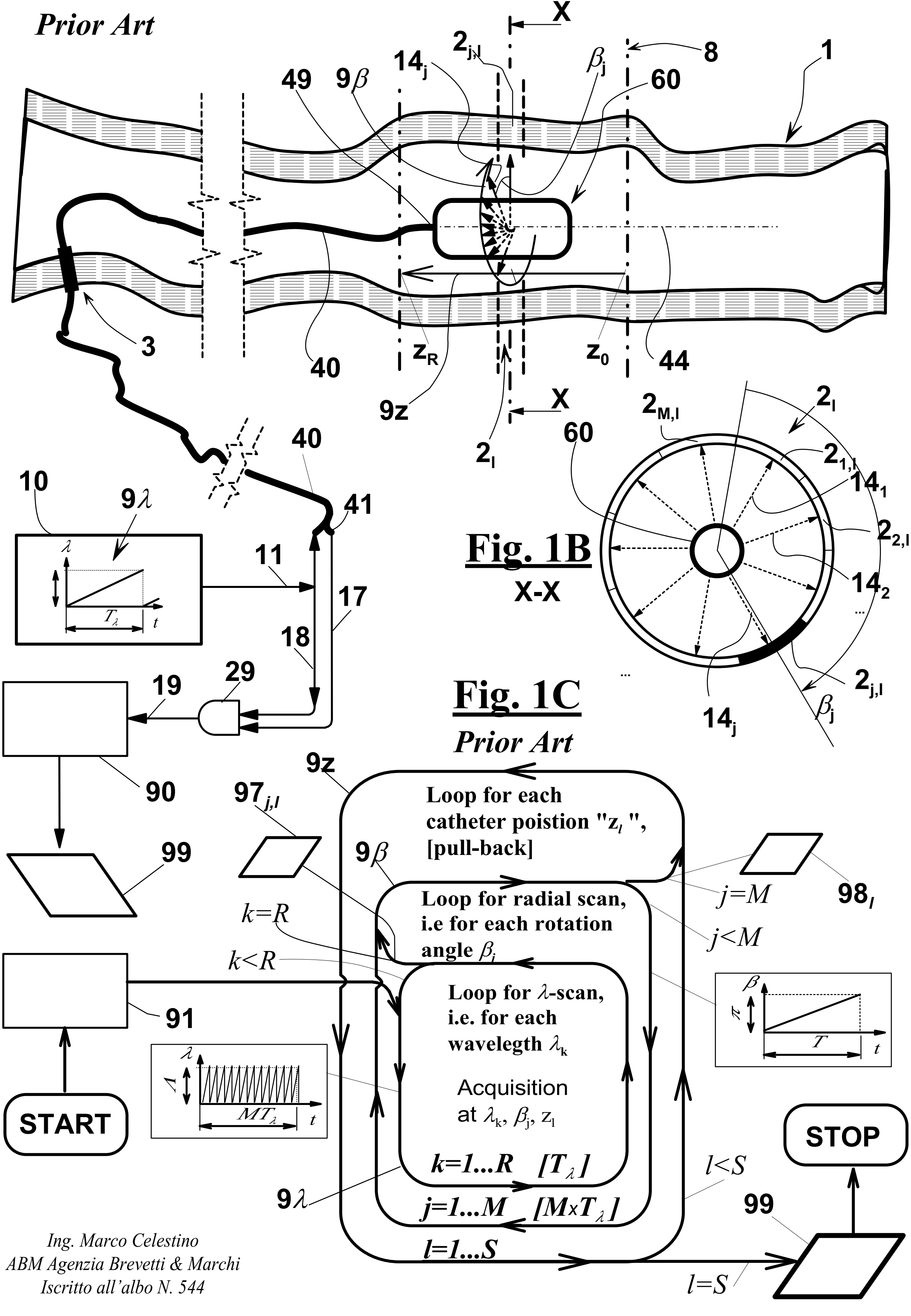

Fig. 1A

Prior Art

Fig. 1B

X-X

Fig. 1C

Prior Art

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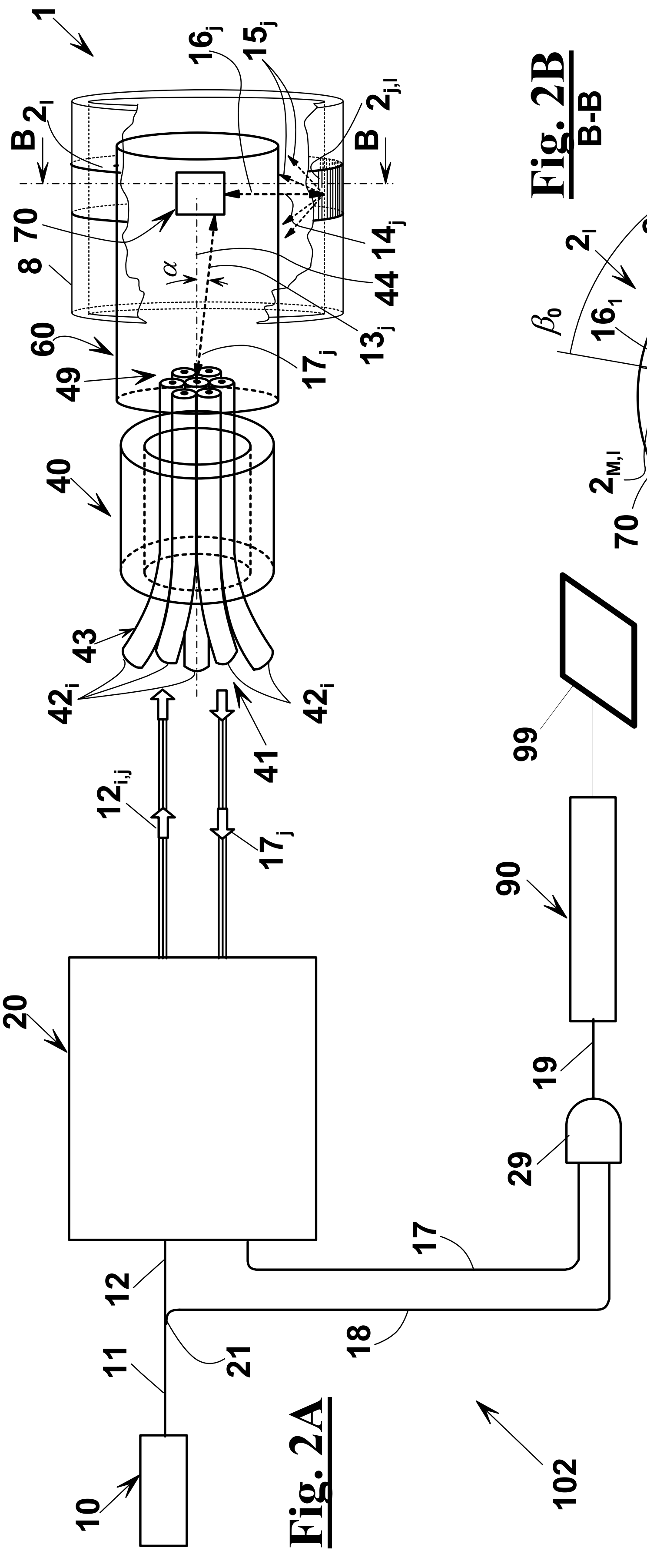

Fig. 2A

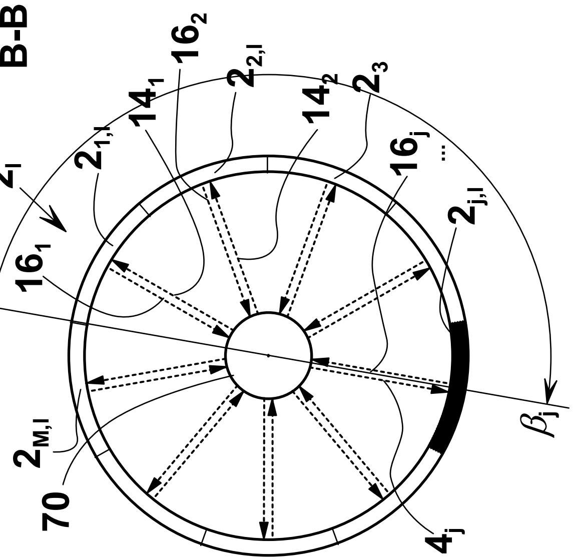

Fig. 2B
B-B

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Fig. 2C

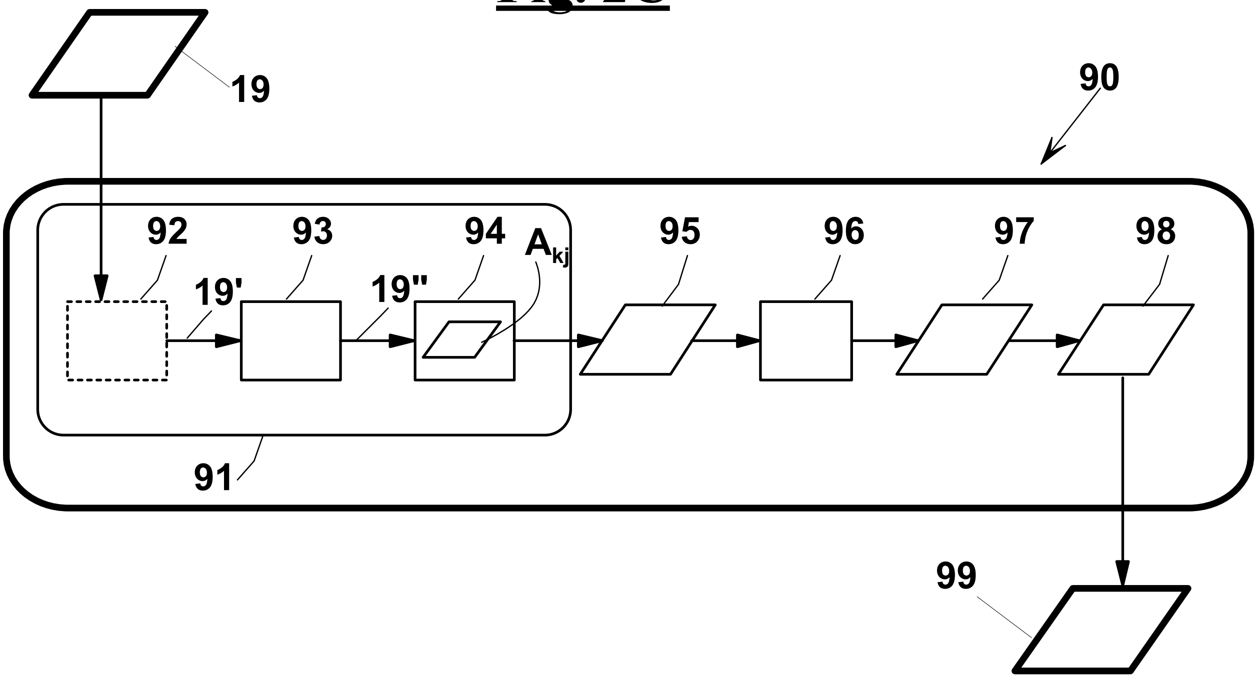
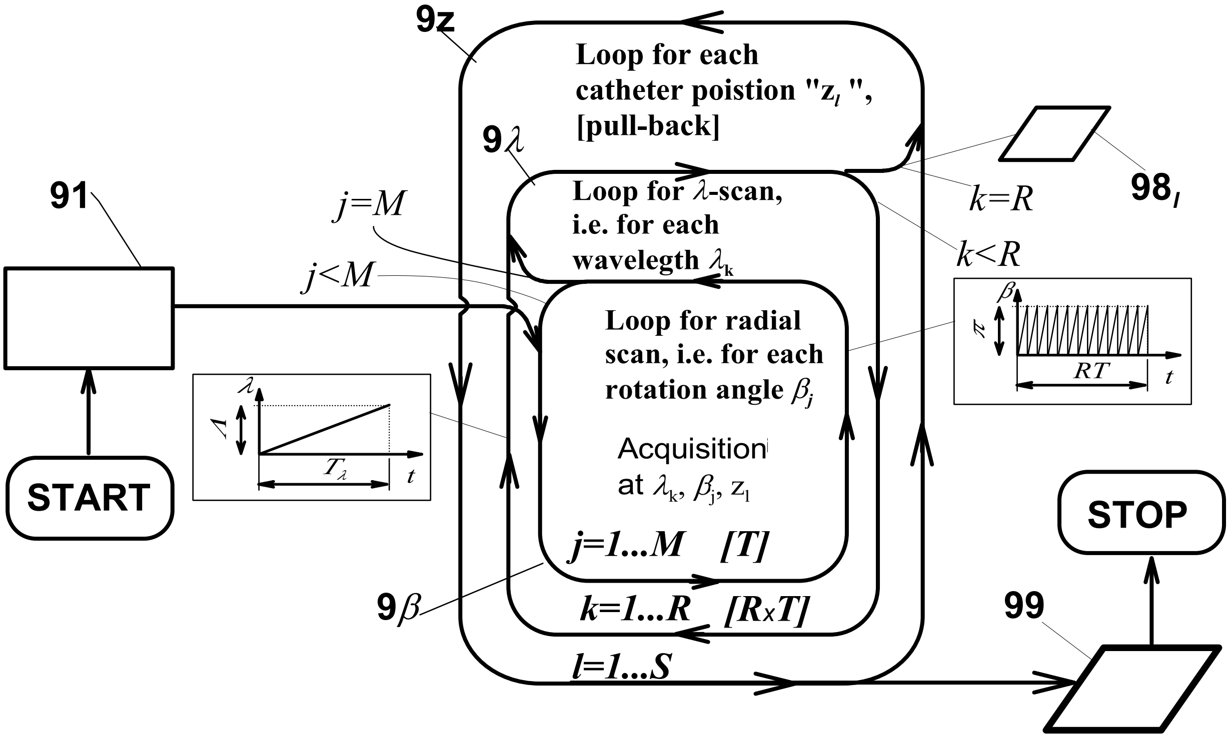


Fig. 2D



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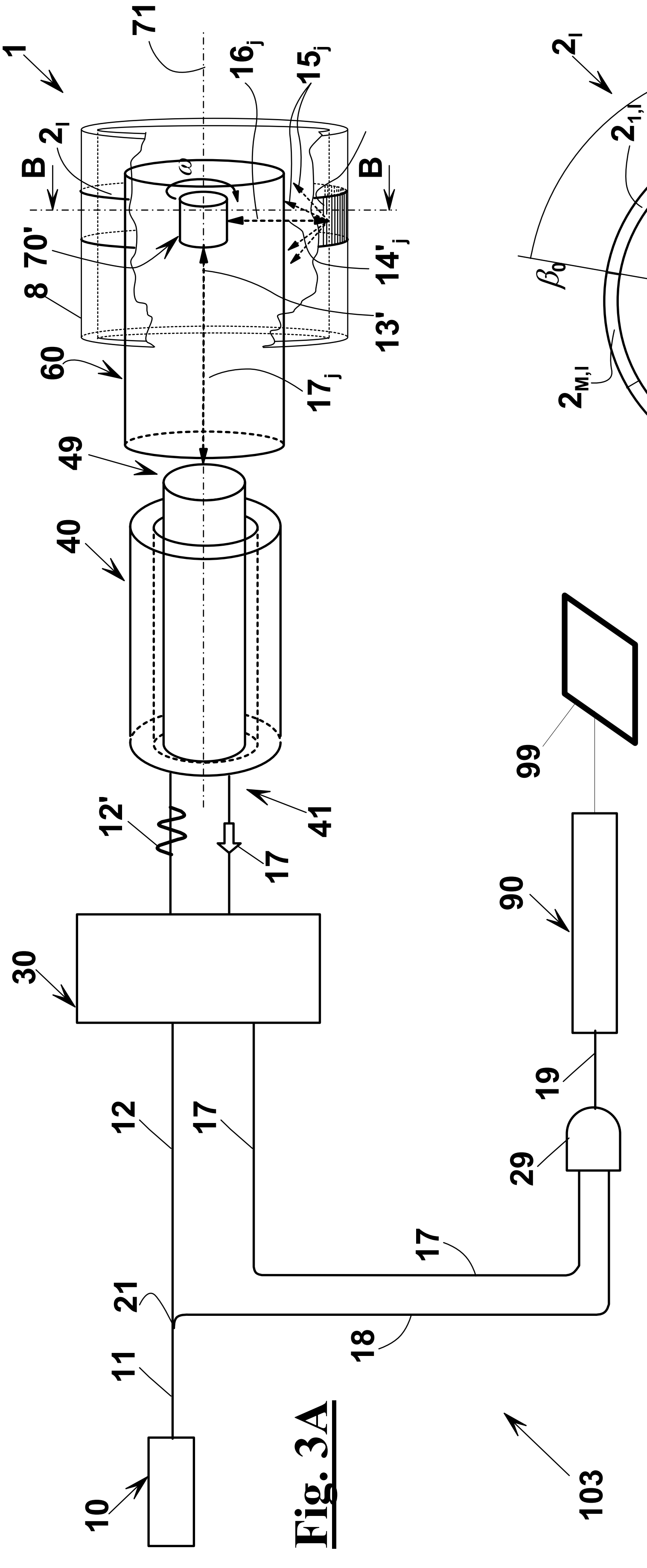

Fig. 3A

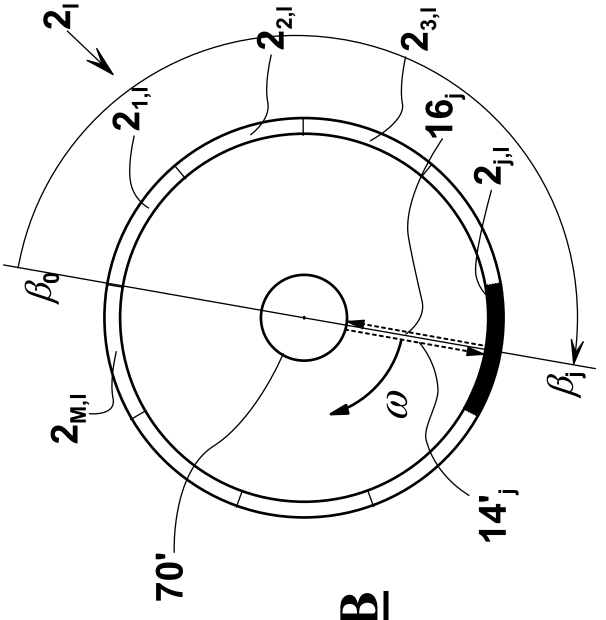

Fig. 3B
B-B

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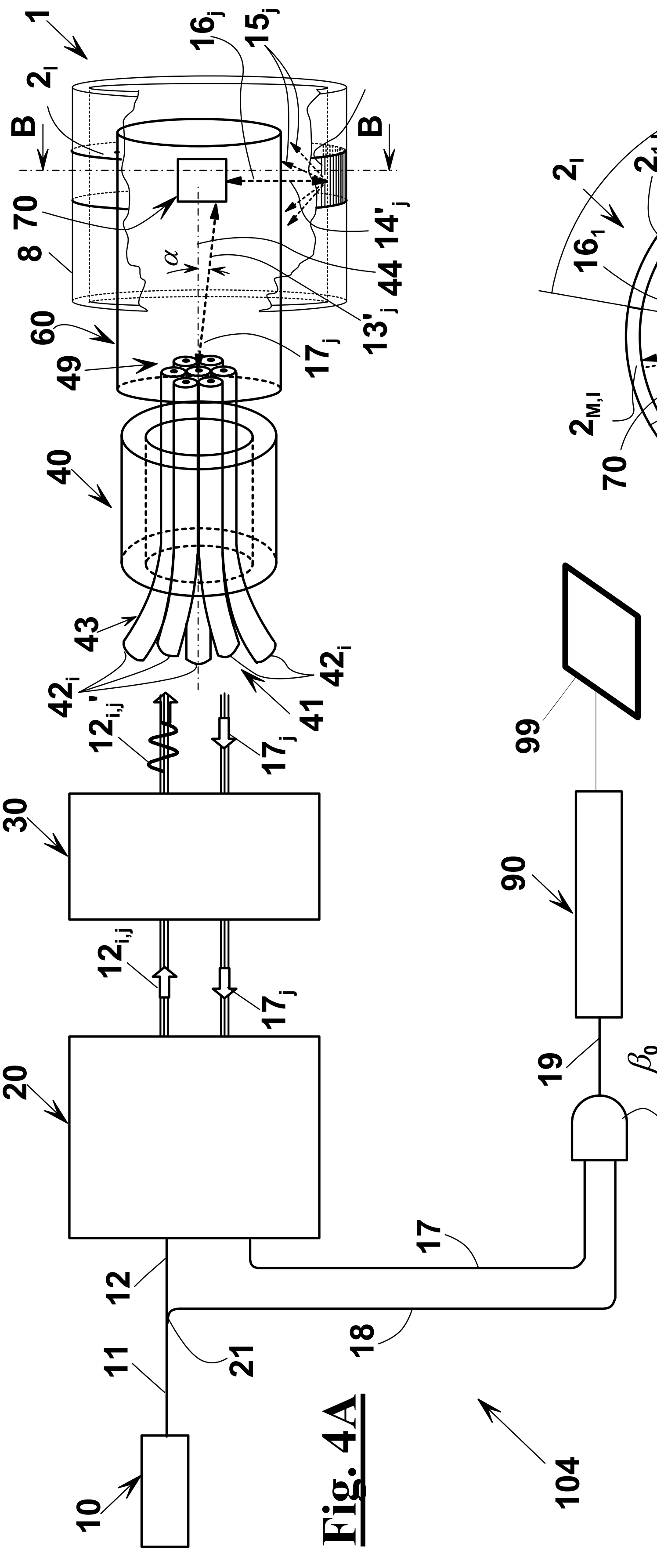

Fig. 4A

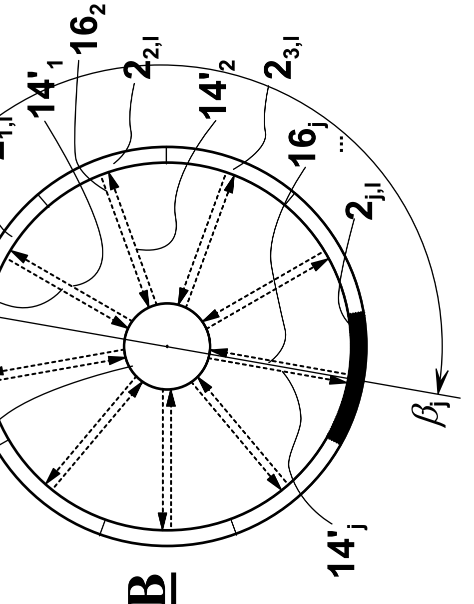

Fig. 4B
B-B

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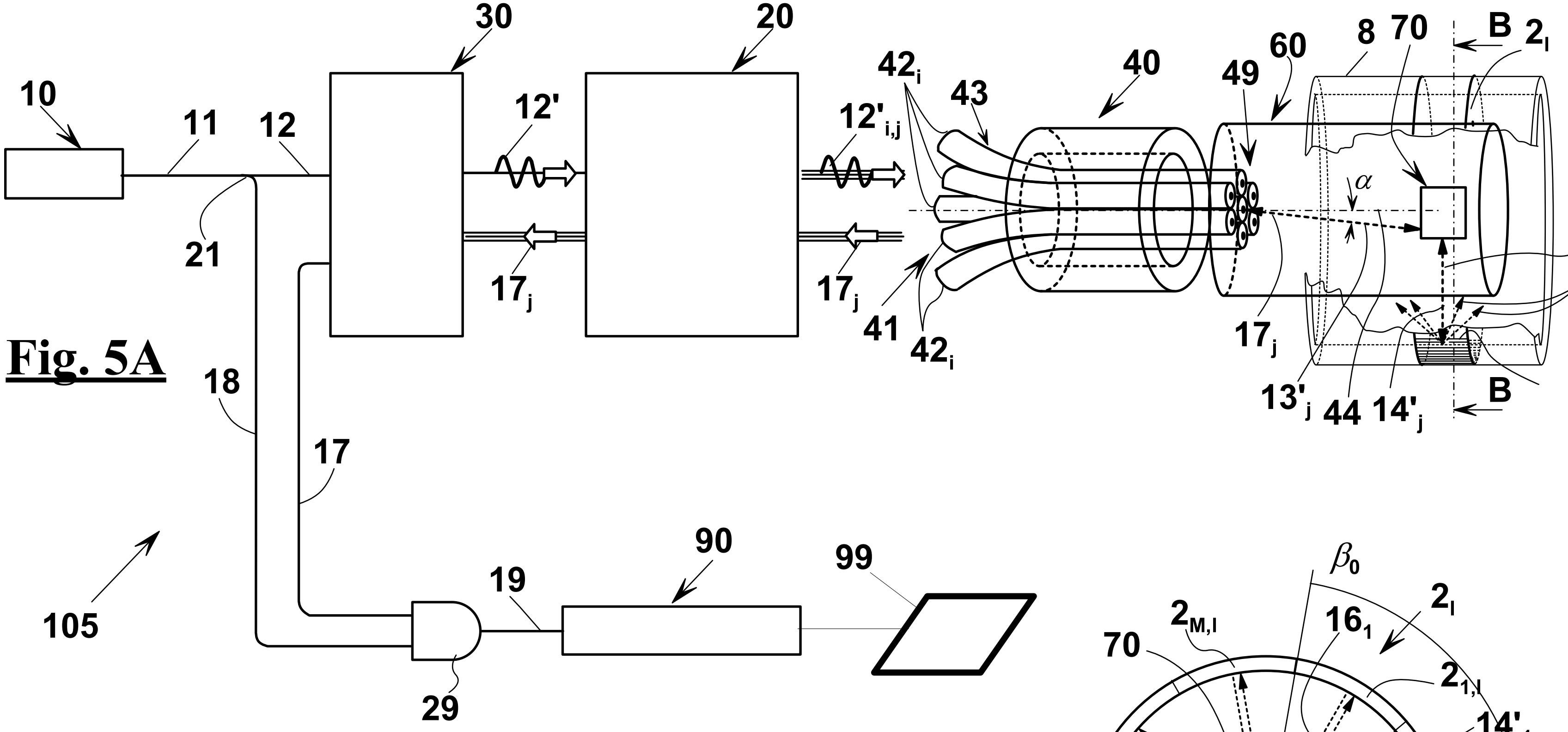

Fig. 5A

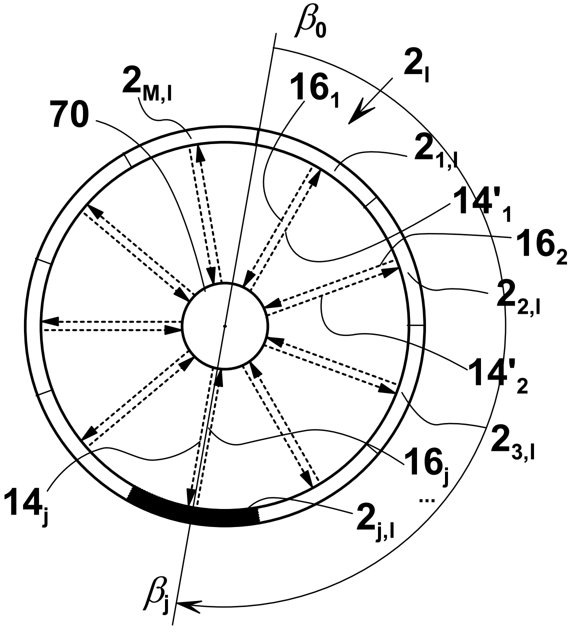

Fig. 5B
B-B

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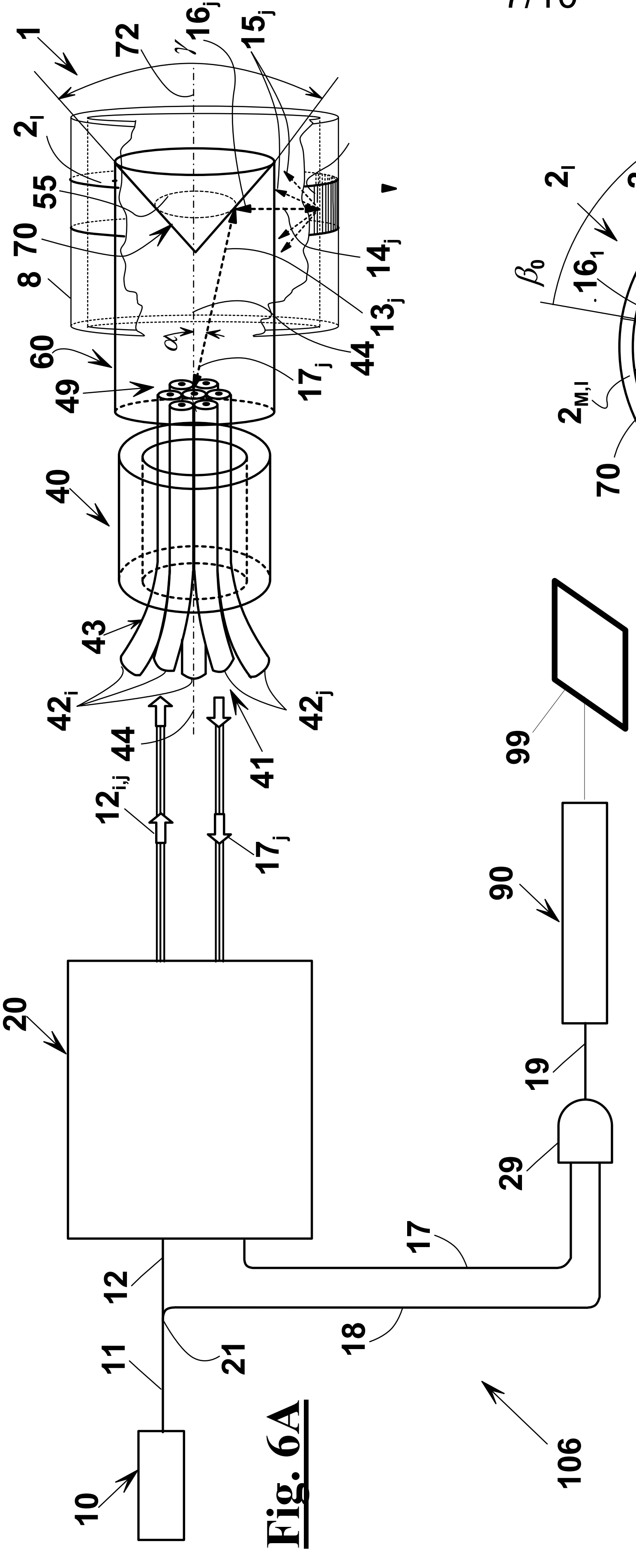

Fig. 6A

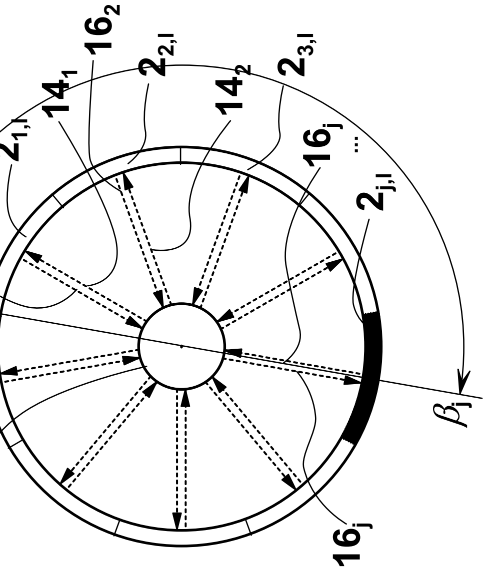

Fig. 6B
B-B

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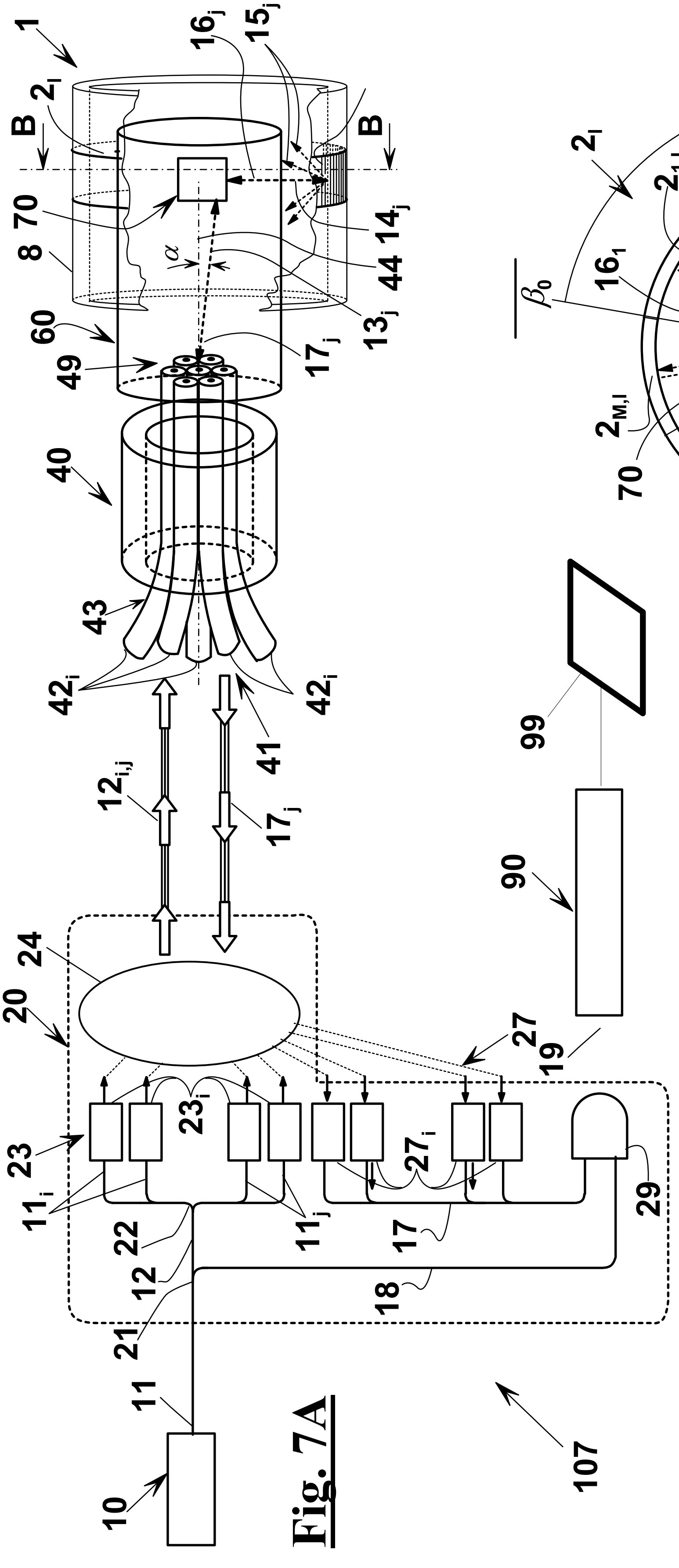

Fig. 7A

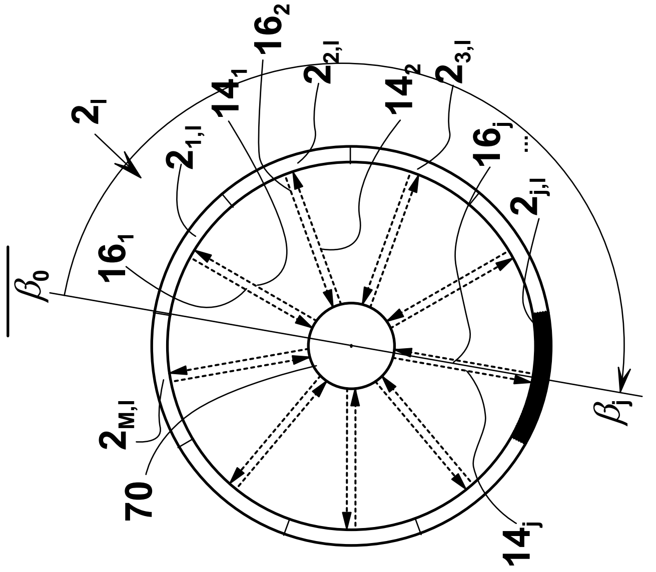

Fig. 7B
B-B

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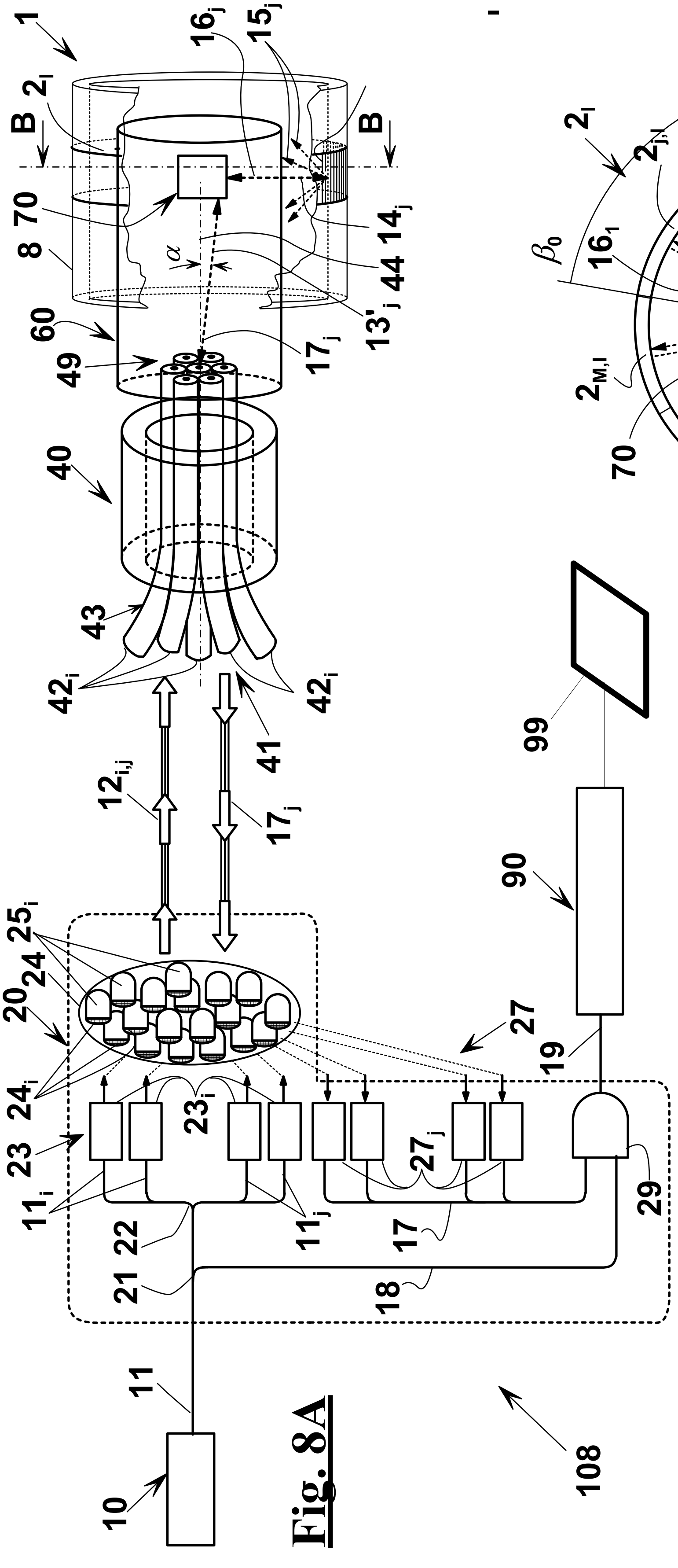

Fig. 8A

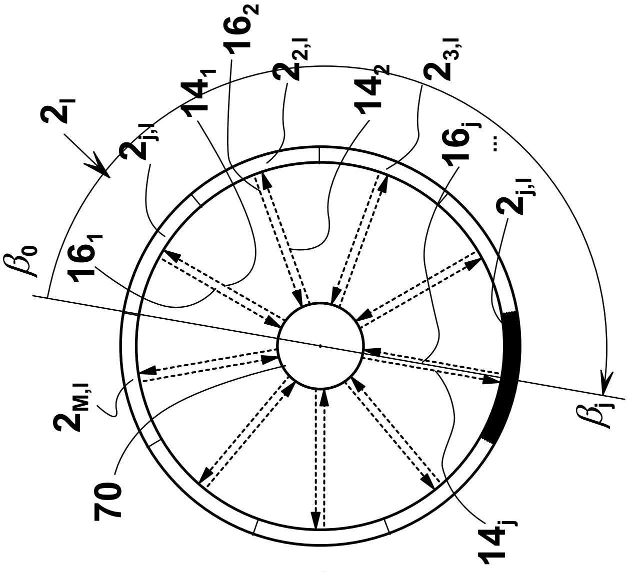

Fig. 8B
B-B

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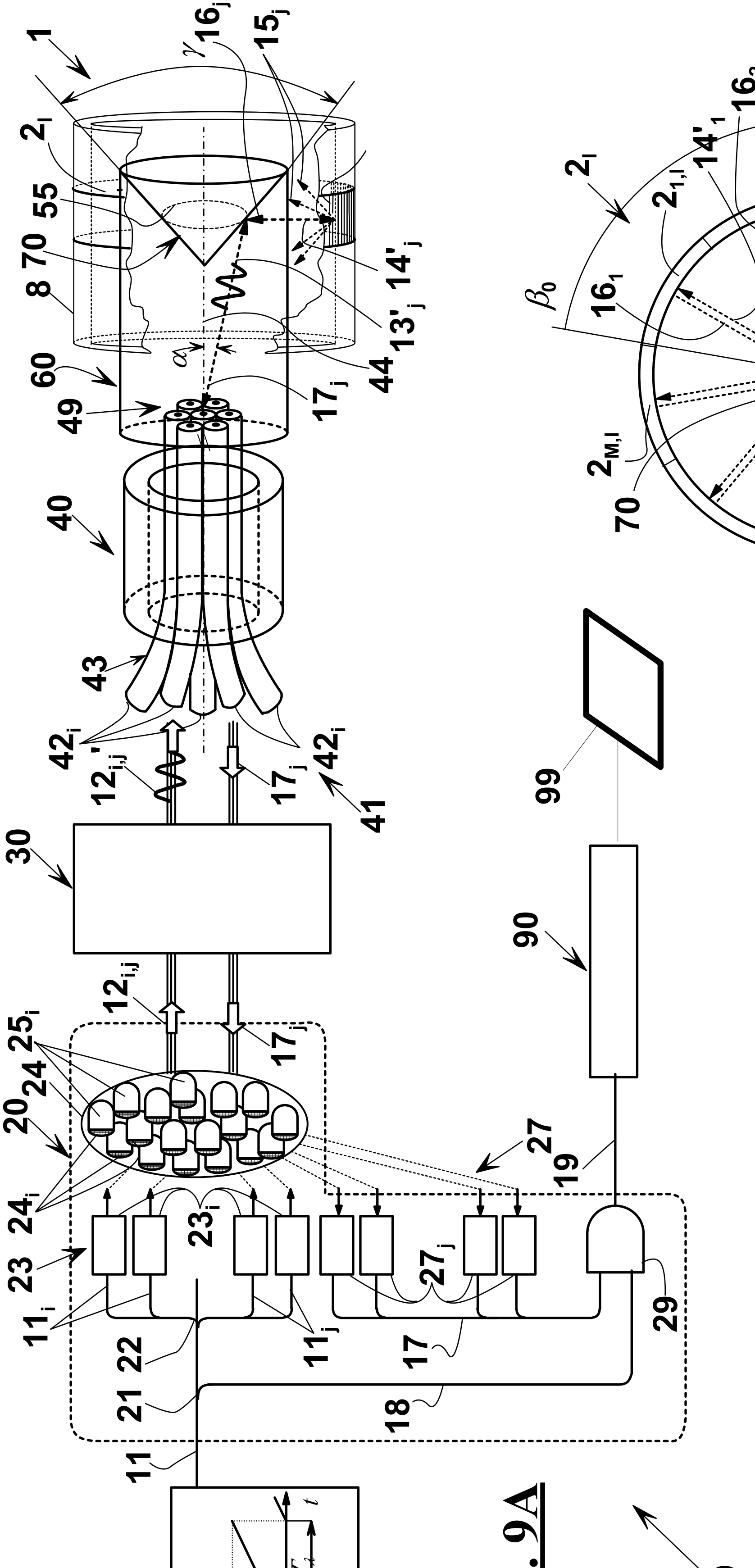

Fig. 9A

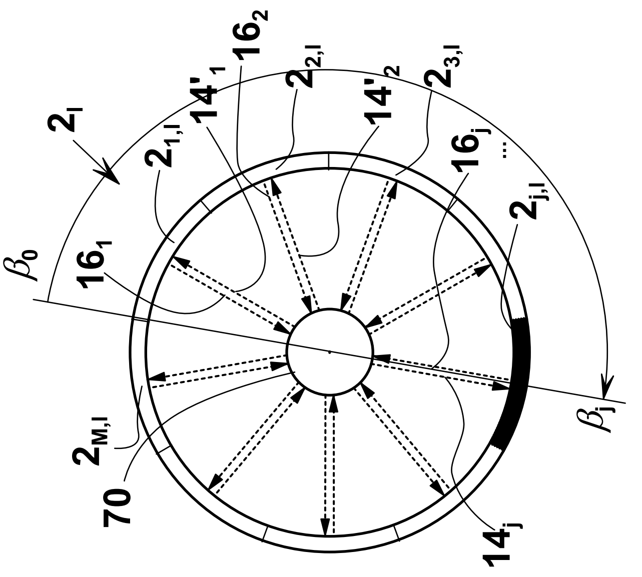

Fig. 9B
B-B

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