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Sanders

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(54) **HIGH-SPEED SPECTROGRAPHIC SENSOR FOR INTERNAL COMBUSTION ENGINES**

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G01B 9/02 (2006.01)

(52) **U.S. Cl.** **356/451**; 356/450

(58) **Field of Classification Search** 356/451, 356/320, 450

See application file for complete search history.

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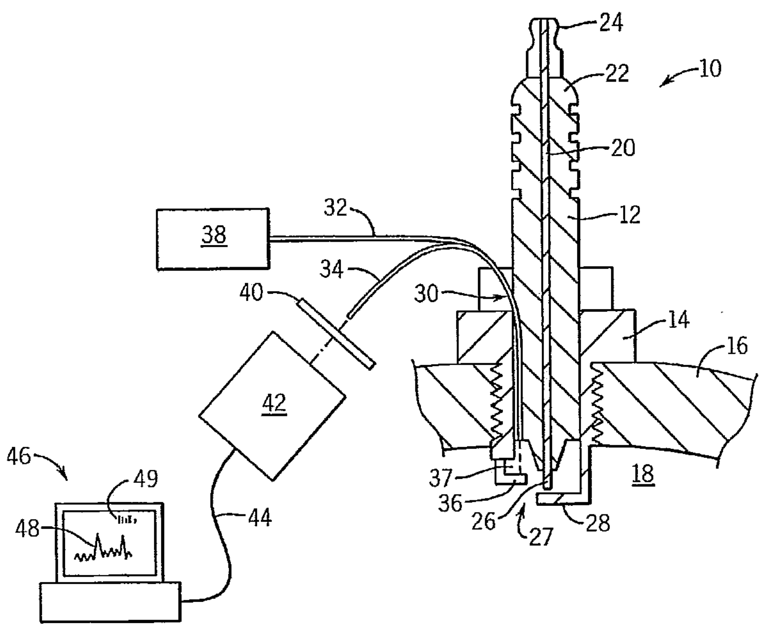
(57) **ABSTRACT**

A high-speed absorption spectrographic system employs a slit-less spectroscope to obtain high-resolution, high-speed spectrographic data of combustion gases in an internal combustion engine allowing precise measurement of gas parameters including temperature and species concentration.

21 Claims, 2 Drawing Sheets



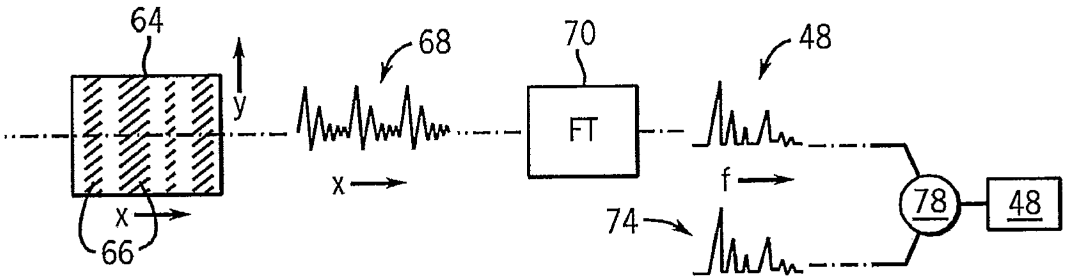


FIG. 3

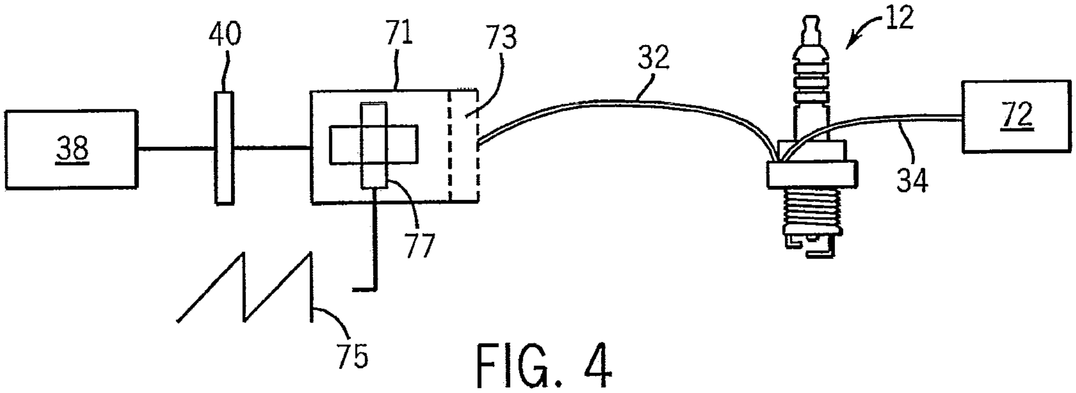


FIG. 4

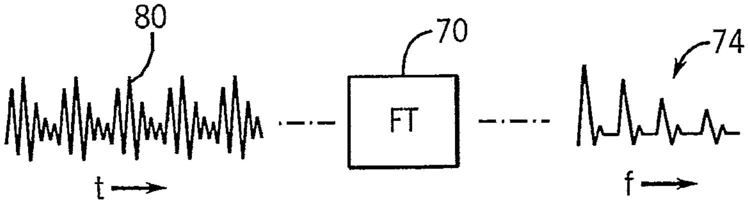


FIG. 5

It is thus another aspect of at least one embodiment of the invention to provide for measurement in the vicinity of the spark in operating the internal combustion engine.

These particular objects and advantages may apply to only some embodiments falling within the claims and thus do not define the scope of the invention.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** is a cross-sectional view of a modified spark plug holding a light guide for receiving light to interact with combustion gases and transmitting the light back to a spectroscope for high-speed analysis;

FIG. **2** is a block diagram of a spatial heterodyne spectrometer suitable for use as the spectroscope of FIG. **1**;

FIG. **3** is a diagram of the process steps of converting an image from the spatial heterodyne spectrometer into a spectrum and in performing signature matching;

FIG. **4** is a block diagram of the alternative embodiment of the invention using the spark plug of FIG. **1** but employing a Fourier spectrometer upstream from the spark plug; and

FIG. **5** is a figure similar to that of FIG. **3** showing those steps of signal analysis in the embodiment of FIG. **4** that differ from the embodiment of FIG. **1**.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT

Referring now to FIG. **1**, a high-speed spectrographic sensor **10** of the present invention provides for a modified spark plug **12** that may be fit to a combustion chamber **18**. In the manner of conventional spark plugs, the spark plug **12** may provide a conductive threaded flange **14** fitting within a corresponding threaded bore in the wall **16** of the combustion chamber **18**, providing a seal therewith.

The spark plug **12** provides a center electrode **20** coaxially within a ceramic insulator **22** and passing from outside of the chamber **18** where it is accessible at a high-voltage terminal **24** to inside the chamber **18** where it extends out of the insulator **22** as an electrode tip **26**. A ground electrode **28** extends from the flange **14** into the combustion chamber **18** to a point opposite the electrode tip **26** across a spark gap **27** in a manner known in the art.

The insulator **22** or threaded flange **14** also holds a light guide **30** passing through the insulator **22** or threaded flange **14** from outside the combustion chamber **18** to a point within the combustion chamber **18** near the spark gap **27**. The light guide **30** may be, in a preferred embodiment, two adjacent optical fibers **32** and **34**, one for carrying light into the combustion chamber **18** and one for carrying light out of the combustion chamber **18** for sensing.

The fiber **32** carrying the light into the combustion chamber **18** may receive light from a broad spectrum light source, such as an incandescent bulb in the form of a quartz tungsten-halogen lamp, or a wideband LED or broadband laser, providing substantial energy in the range of 2000 nm to 3000 nm and preferably in a range of 2400 nm to 2600 nm and having a known spectrum.

A mirror **36** is positioned across a gap **37** from the point where the light guide **30** terminates in the combustion chamber **18**. The mirror **36** is positioned so that light passing through optical fiber **32** exits the light guide **30** and passes across the gap **37** to strike the mirror **36**, to be reflected back across the gap **37** and be received by fiber **34**. The optical path through the gap **37** may be as great as 10 mm to allow the light to interact with combustion gases in the region of the electrode tip **26**.

Light received from optical fiber **34**, after interacting with the combustion gases, passes through a filter **40**, for example, a band limiting filter of the desired frequency range (e.g. 2400-2600 nm). The filtered light is then received by a spectrometer **42** which in the preferred embodiment is a spatial heterodyne spectrometer.

The spectrometer **42** provides a digitized output **44** received by a computer **46**. The computer executes a program to display a high-resolution absorption spectrum **48** (based on known or measured spectrum of light source **38**) extracted every 100 μs and no less than every 1000 μs and consisting of hundreds of resolved frequency points and no less then twenty resolved frequency points. The computer **46**, operating according to the stored program, may also identify a quantitative parameter value **49**, being for example a temperature of the combustion gases or a species mole fraction such as water concentration or other similar measurement, as will be described.

Referring now to FIG. **2**, the spatial heterodyne spectrometer **42** provides an open aperture and high-speed response made possible by its efficient use of minor energy obtained through fiber **34**. Spectrometers of this type are described in U.S. Pat. No. 5,059,027, issuing Oct. 22, 1991, assigned to the assignee of the present invention, and hereby incorporated by reference. Such a spectrometer receives a light signal **50** from the fiber **34** and collimates this light using an optical assembly **52** to provide for a beam **53** having generally an aligned wavefront **54**.

A dispersive optical system **56** tips the wavefronts **55** of each of multiple frequency component in the light signal **50** (only two shown) to an angle α dependent on the wavelength of that frequency component. The wavefront-modified beam **58** is then received by an imaging optical assembly **60** to project an image on a solid-state image detector **62** such as an extended InGaAs line scan camera commercially available from Xenics Leuven, Belgium. The signal from the solid-state image detector **62** may be digitized and sampled per block **63** to produce an image **64** at approximately 1000 times per second or as much as 10,000 times per second.

Referring now also to FIG. **3**, the image **64** from the solid-state image detector **62** will contain a series of bands of different intensities **66** caused by interference in the image produced by the constructive and destructive interference of the wavefronts **55** as tipped by dispersive optical system **56**. The information of this image **64** may be collapsed to a single dimension (x) to produce a spatially dependent signal **68** with improved signal-to-noise ratio that better utilizes all of light energy from the fiber **34** both improving the speed and the resolving power of the spectrum.

This signal **68**, when operated on by the Fourier transform **70**, as may be implemented in the computer **46** of FIG. **1**, produces a high-resolution spectrum **48** providing resolvable points for more than 100 different frequencies. The high-resolution spectrum **48** may be compared to spectrum **74** of a library **76** of different signature spectra **74** by a correlator **78**, where each signature spectra **74** is associated with a known physical parameter that is to be extracted. For example, the multiple spectra **74** may each represent measurements of combustion gases at a different temperature. Alternatively the multiple spectra **74** may each represent a measurement of a different water concentration or another species concentration.

The correlator **78** finds the best correlation between high-resolution spectrum **48** and each of spectra **74** to output a measured temperature or other quantitative parameter value **49** as shown in FIG. **1**, according to the parameter associated with the most highly correlated spectra **74**.

(b) introducing light at multiple frequencies having wavelengths less than 3000 nm into the light guide to interact with combustion gases; and

(c) receiving light from the plug through the light guide at a slit-less spectroscope attached to the light guide to receive light from the light guide directly also without an intervening slit;

(d) spatially separating multiple light frequencies as received simultaneously by an optical system of the spectroscope after passage through the combustion chamber to permit simultaneous monitoring of the multiple frequencies at different spatial locations; the spectroscope distinguishing strength of no less than 20 multiple frequencies of the light at a rate of no less than 1000 times per second after interaction with the combustion gases.

13. The method of claim **12** wherein the determining spatially heterodynes the light received after interaction with the combustion gases to determine attenuation of the multiple frequencies.

14. The method of claim **12** further including outputting temperature within the combustion chamber from the strengths of the multiple frequencies.

15. The method of claim **12** further including outputting water concentration within the combustion chamber from the strengths of the multiple frequencies.

16. The method of claim **12** further including matching the strength of the multiple frequencies to multiple signatures with similar multiple frequencies and representing known different physical parameters to deduce a physical parameter within the combustion chamber.

17. The method of claim **12** wherein the light includes frequencies having wavelengths substantially within a range of 2400-2600 nm.

18. The method of claim **12** wherein the attenuation of no less than 100 multiple frequencies is determined.

19. The method of claim **12** wherein the attenuation of the multiple frequencies is determined no less than 10,000 times a second.

20. The method of claim **12** further including measuring and time-modulating the multiple frequencies before the light interacts with the combustion gases; and

demodulating a time signal derived from a strength of the multiple frequencies to distinguish the strength among the multiple frequencies after interaction with the combustion gases.

21. The method of claim **12** further including providing an ignition spark in the vicinity of the light guide within the combustion chamber.

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