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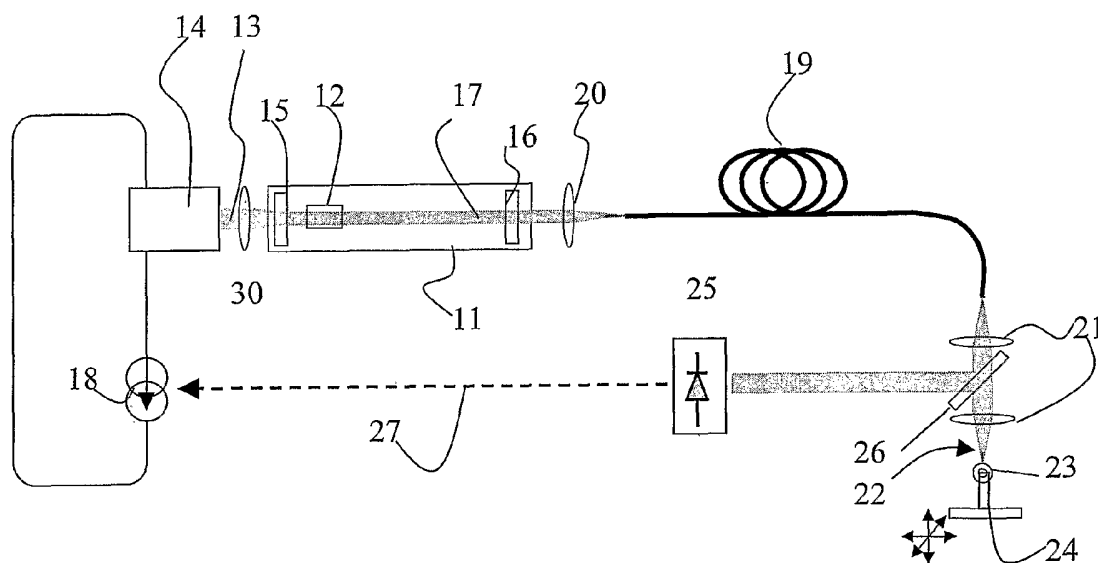
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(54) Title: SPOT WELDING LASER APPARATUS AND METHOD THEREOF



(57) Abstract: Laser spot welding apparatus of the type generating a pulsed laser beam, comprising a pumping source (14) arranged to generate a pulsed pumping beam (13) for a resonant cavity (12) comprising an active medium (11). According to the invention said pumping source (14) comprises a solid-state laser diode assembly.

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**SPOT WELDING LASER APPARATUS AND METHOD THEREOF**

The present invention relates to a spot welding apparatus of the type which generates a pulsed laser beam, comprising a pumping source generating a pulsed pumping beam for a resonant cavity comprising an active means, and a relative pumping method for a laser welding apparatus to obtain laser spot welds (spot welding).

Solid-state laser spot welding, by which a pulsed laser beam is fed onto the workpiece to be welded, is well known and widely used in numerous metallurgical applications. In this respect, this method is particularly suitable for welding without the use of low-melting weld material, which has the drawback of altering the metallurgical properties of the article to be welded, in fields such as jewellery or the production of bio-compatible metal components and devices.

There has recently been a considerable increase in high-precision spot welding, in which the laser energy has to be focused in a controlled and repeatable manner onto a weld spot of very small dimensions (tens of microns); a non-limiting example of such an application is the welding of jewellery articles formed of ultra-thin wire, the production of electronic and electro-optic components, of biomedical components, and of precision mechanisms for example for clock movements.

Laser spot welding apparatus based on Nd:YAG crystal laser sources are known, in which pumping is by means of flash lamps able to generate laser pulses with an energy of several joules and a duration of some milliseconds. Although such performance is more than adequate for making spot welds with optimal mechanical strength characteristics, such equipment presents intrinsic non-ignorable limitations in terms of precision and repeatability of the spatial and temporal profiles of the welding pulse. Such limitations are apparent in applications in which the precision of the weld spot plays a basic role, and arise mainly because of lamp pumping.

In this respect, known state of the art devices use pumping chambers in which one or two flash lamps with noble gases feed very high energy light pulses to the laser medium. The lamps are fed with current pulses of some hundreds of Amperes and voltages of the order of some hundreds of Volts for some milliseconds. Given the quantities involved, control of the instantaneous power

supplied to the lamp by the power supply device is consequently very difficult; it rarely achieves better than 5-10% amplitude precision and presents intervention time constants of the order of a fraction of a millisecond. The energy associated with the laser pulse can vary from pulse to pulse and is difficult to regulate when time scales shorter than a millisecond are involved. This determines evident regulation problems for welds on minute metal articles where sub-millisecond temporal dynamics can alter the welding result.

The electric power supplied to the lamp is converted into a luminous arc the shape of which, pulse after pulse, follows a statistical pattern which is reflected in a fluctuation of the spatial distribution of the laser gain. This effect produces a statistical fluctuation of the aiming direction of the laser beam, and of the energy distribution within the spot weld.

These limitations become prohibitive in, for example, the spot welding of mechanical clock components with dimensions of the order of 0.1 mm: fluctuations of the order of 10% of the pulse energy can degrade the weld or even irreparably damage the parts to be welded.

A further problem for the repeatability and uniformity of the spot weld in the long term lies in the fact that, after some millions of pulses, the performance of the arc lamps degrades to the point that they have to be replaced, so imposing machine maintenance and downtime costs which cannot be ignored. Moreover, continuous replacement of the pumping lamps finally leads to a reduction in the reliability of lamp-pumped laser welding systems because of the frequent exposure and contamination of the delicate optical surfaces of the laser cavity. For this reason, and because of the statistical variability in the performance of individual arc lamps, a spot welding system based on lasers pumped by lamps requires numerous setting operations and maintenance during its entire life, particularly in applications in which precision and repeatability of the spatial and temporal shape of the laser pulse is required.

Other problems directly limit the precision of the welding process. To maximize pumping efficiency, i.e. absorption of the pumping light into the active medium, bars of active laser medium of large cross-section are used; consequently, a large number of laser modes can oscillate within the cavity; in this manner the laser beam generated has poor spatial quality and therefore cannot be focused onto small dimensions. In various microwelding applications on very small-dimension components, the laser light hence cannot be totally

transferred to the workpieces to be welded. A typical example is the welding of precious metal chain rings on automatic jewellery machines; by cutting, bending and welding operations, these machines transform a continuous gold (or other precious metal) wire of between 0.1 and 1 mm cross-section into a chain of interconnected rings. If the wire diameter is less than 0.2 mm, the welding area becomes less extended than the typical laser focal spot; consequently, part of the laser pulse energy is dispersed around the workpiece, with two contraindications: the system has to deliver much more energy than effectively required for a good weld, while the dispersed energy causes damage in areas of the workpiece not involved in the process, or even wear of the tools used to position the ring to be welded. For the same reason, the spot weld produced by this method is characterised by a very large region (compared with the wire cross-section) of material altered by the application of heat (the so-called heat affected zone, HAZ), with obvious contraindications of mechanical and aesthetic dishomogeneity.

Finally, the efficiency of the process of energy transfer from the arc lamp to the bar of active laser medium is very low (just a few percentage points), the residual energy being dissipated as heat; the laser bar and lamp have therefore to be cooled by circulating cooling fluid, with all the reliability limits and dimensions that such cooling systems involve.

The object of the present invention is to provide a laser welding apparatus of improved efficiency, which provides effective spatial and temporal pulse control, even in association with sub-millisecond temporal dynamics.

This object is attained, according to the present invention, by a laser welding apparatus and a corresponding pumping method which have the characteristics specifically defined in the ensuing claims.

Briefly, the proposed solution provides an apparatus able to generate high energy laser pulses of high spatial quality, comprising a solid-state laser cavity of discrete elements which receives a pumping beam via semiconductor laser diodes. The pumping is configured such as to ensure high repeatability of welding performance together with high efficiency, simplicity and reliability.

Further objects, characteristics and advantages of the present invention will be apparent from the ensuing detailed description and from the accompanying drawings, provided by way of non-limiting example, in which:

Figure 1 is a basic scheme of the laser spot welding apparatus according to the

invention;

Figure 2 is a basic scheme of a variant of the laser spot welding apparatus of Figure 1.

The proposed solution uses a laser source comprising an assembly of solid-state laser diodes, arranged to generate welding pulses provided with high energy, spatial quality, stability and repeatability, such as to exceed the precision limits intrinsic in the laser spot welding technology based on currently commercially available lamp-pumped systems.

The use of such an assembly of solid-state laser diodes also makes it possible to considerably reduce the amount of energy required to make a spot weld, while at the same time obtaining a simplification in the laser system and a further increase in its reliability.

Figure 1 shows a basic scheme of the apparatus of the laser spot welding method of the invention.

This apparatus comprises substantially a laser cavity 11, within which there is a solid-state active medium 12. The laser medium 12 receives energy by means of a pumping beam 13, generated by an assembly of semiconductor laser diodes 14.

The laser cavity 11 or resonator comprises a mirror 15 provided with a surface which totally reflects at the wavelength of a laser beam 17 generated by the active medium 12, and a second mirror 16 partially reflecting for the laser beam 17, which hence at least partially transmits the output laser beam 17. The laser medium 12 present within the laser cavity 11 consists of a suitable Nd:YAG crystal. Crystals of Nd:YVO<sub>4</sub> or Nd:GdVO<sub>4</sub> or Nd:YLF or other high efficiency laser medium can also be used, preferably shaped as a cylindrical or parallelepiped bar. The laser crystal of the active medium 12 is housed in a suitable structure, not shown in Figure 1, which performs the double function of mechanical support and dissipator for the heat generated in the bar; this heat can be removed by conduction, or actively by using for example a Peltier element and/or a suitable air heat exchanger. As stated, the active medium 12 receives the pumping beam 13 from an assembly of semiconductor laser diodes 14; this diode assembly 14 is disposed, to the desired power, as a suitable number of rows or matrices, the temperature of which can be controlled or in any event maintained within the intrinsic limits for correct and reliable operation of the apparatus by a solid-state cooling system (Peltier cells) and/or

heat transfer with the ambient air, without using liquid cooling devices. A suitable lens 30, positioned in proximity to the diode assembly 11, conditions the emission of the pumping beam 13, by focusing the rays emitted by the diodes and conveying them onto the active medium 12. The pumping operation can take place laterally, i.e. by traversing faces of the active medium 12 not involved in the laser action, or longitudinally, i.e. along the approximate direction of the laser action and/or through faces involved in the laser action. Longitudinal pumping, which is the pumping scheme shown in Figure 1 and preferred for the implementation of the present invention, enables particularly small controlled sections of active medium to be excited, hence ensuring that all the pumping energy is transferred to a limited number of laser modes within the cavity 11. Consequently longitudinal pumping enables laser emission of high spatial quality (low number of modes) and high efficiency to be obtained, being particularly advantageous in those applications in which weld spots of very small dimensions are required, with diameters for example less than 0.2 mm.

The laser beam 17 emitted by the cavity 11 by means of the diode assembly 14 is characterised by a spatial distribution of well determined and highly repeatable intensity and aiming direction, with great benefit to the precision spot welding process.

The pumping laser diodes for pulse lasers used in the unity 11 present an average life of the order of one billion "pulses", resulting in a maintenance-free operating time about 100 times longer than traditional flash lamps, with obvious beneficial effects on long term reliability and repeatability of the welding system.

The pumping laser diode assembly 14 is powered by a suitable electrical pulse power unit 18. This unit 18 supplies pulses with a maximum current of the order of one hundred Amperes, at relatively low load voltages, i.e. of the order of ten or a few tens of Volts. The electronic components currently available enable pulses of this type to be achieved with control of the instantaneous delivered power to within 1 or 2 percentage points, with characteristic intervention and control time constants of the order of a few microseconds. Such electrical characteristics enable very accurate control of the emitted laser power, at least within 2 or 3%, with a temporal precision of a few microseconds; hence pulses of extreme precision and repeatability can be

obtained with a temporal profile which is not square but instead can be programmed by the user to best aid the welding process.

By virtue of the high temporal and amplitude precision of the pumping pulses the resultant spot weld presents high repeatability, enabling even very thin  
5 articles with cross-sections of the order of a few tens of microns to be welded without rejects.

The generated laser beam 17 is used directly at the exit of the resonant cavity 11, from which it is conveyed towards a workpiece to be welded, indicated by the reference numeral 23 in Figure 1, by means of a suitable chain of optical  
10 means which reflect or transmit at the laser wavelength. These optical means for conveying the laser energy can comprise a suitable optical conveying fibre 19, to which the laser beam 17 is coupled using optics 20 for its launch into the fibre (such as one or more lenses). The optical fibre 19, the use of which is however optional, is associated, at that end close to the workpiece 23 to be  
15 welded, with focusing lenses 21 for the laser beam 17. The use of the optical fibre 19 presents two advantages: it makes the position of the welding point mechanically independent of the position of the laser cavity and of the laser diode assembly 14, and homogenizes the shape of the laser beam 17 at the weld spot, to make the geometrical appearance of the laser beam 17 at its  
20 output partially independent of the spatial distribution of the laser beam 17 entering the fibre. The use of a laser source of improved spatial quality allows efficient injection into optical fibres of very small core, for example of diameter less than a hundred microns, so enabling the laser radiation to be focused without aberration on a weld spot of small dimensions comparable to the  
25 diameter of the optical fibre core itself.

The workpiece 23 to be welded, which is to receive the welding pulse, is positioned at a focal point 22 of the laser beam 17, determined by the focusing optics 21, by means of a micrometric mechanical positioning system 24: the positioning system 24 can be manual or automatic.

30 Alternatively, one or more elements of the optical transport and focusing chain for the laser beam 17 can be made movable, to move the focal position of the welding pulse on the workpieces to be welded. An example of this is given in the description of Figure 2.

Figure 1 shows a suitable detector 25, for example a photodiode, positioned  
35 downstream of the optical path, as close as possible to the welding field

defined by the workpiece 23 to be welded, to detect the variation in the laser power reaching the weld spot during the pumping pulse given by the pumping beam 13. Alternatively, this detector 25 can be positioned downstream of the source, i.e. of the laser diode assembly 14. The detector 25 measures a sample of the output power of the laser beam 17 by withdrawing a substantially negligible quantity of the radiation (usually less than 1%) of the laser beam 17 by reflection by a suitable optics 26, for example a partially reflecting mirror, almost completely transparent at the laser wavelength. Alternatively the detector 25 can detect the laser light diffused along the optical path without the presence of an optics dedicated to sampling the laser beam 17.

A suitable electronic circuit 27, programmable by the user, allows feedback control of the temporal power profile of the generated laser beam 17, using the detector 25 as instantaneous sensor and acting on the power supply 18 to the laser diode assembly 14 to shape the incident temporal profile at the weld spot in accordance with a profile chosen by the user. This mode of operation with feedback control of the emitted power enables improved repeatability of the laser pulses to be obtained, which can reach the weld spot within 1% of the power value, on a temporal scale of a few tens of microseconds, this repeatability being maintainable for the entire useful life of the system. In this respect, if welding is effected at an energy value lower than the absolute maximum available at the source, there is a certain margin that can be used to increase the supply power to the system to compensate a possible degradation of the output energy due to ageing of the pumping diodes or to wear of the optics; in this case the optical feedback renders the output power independent of ageing effects, which are automatically balanced.

By virtue of the narrow emission band and the high energy efficiency of the laser diodes of the assembly 14, by using an active medium with high emission efficiency, such as not limiting Nd:YVO<sub>4</sub>, high energy of the laser pulse can be obtained with overall efficiency on the absorbed electrical energy greater than 20%. Such high efficiencies mean that only small quantities of heat have to be removed from the laser welding apparatus, hence a solid-state cooling and heat dissipation system can be used, for example with Peltier elements or simply with finned metal dissipators. The reliability and compactness of the system, together with its energy efficiency are hence considerably increased. The mechanical rigidity of the pumping system based on the laser diode assembly

14 and the absence of a turbulent cooling liquid stream eliminate any possibility of spatial fluctuation of the pumping beam 13, so improving by some orders of magnitude the aiming stability and repeatability of the spot weld in the short term. The small aiming instabilities which can occur in the long term due to ambient temperature variations can be easily eliminated if a  
5 temperature control system based on Peltier cells is used to control the temperature of the laser diode assembly 14.

Figure 2, as stated, shows a variant of the apparatus of Figure 1. As can be seen, the resonant cavity 11 of said variant receives the pumping beam 13  
10 laterally, to emit the laser beam 17 in a direction perpendicular to said pumping beam 13.

The variant of Figure 2 also comprises mirrors 29 and 30 positioned in the optical path of the laser beam 17, downstream of the laser cavity 11, and rotatable about an axis to move the focal point 22 within a plane, a focusing  
15 lens 31, if required, being translatable vertically to translate the focal point 22 vertically.

The translation movements can be achieved by suitable translation stages not shown in Figure 2 (for example stepping, linear or other motors), the rotation movements of the mirrors 29 and 30 being achieved using for example galvo  
20 motors similar to those used in common scanning heads for laser marking.

If deflection mirrors are used for the mirrors 29 and 30, the focusing lens 31 can be positioned either upstream or downstream of these mirrors. Precise positioning of the workpiece 23 to be welded or of the focus 22 of the laser welding beam 17 can be aided by the presence of a suitable aiming system,  
25 comprising a visible low power laser 34 feeding an aiming beam 35 which propagates coaxially to the laser welding beam 17 via a suitable dichroic mirror 36. Operation of the visible laser 34 can be enabled with the laser diode assembly 14 turned off, to identify downstream of the focusing optics 29, 30, 31 the precise point in which the pulses will be focused, i.e. the focal point  
30 22.

The characteristics of the present invention are clear from the foregoing description, as are its advantages.

Advantageously, the described laser spot welding apparatus uses a solid-state laser pumped by pulse-powered laser diodes, enabling the precision and  
35 repeatability of the welding process to be increased, in that it generates laser

pulses for spot welding with high spatial quality of the beam, with very high aiming stability and with a virtually constant spatial intensity distribution, together with a temporal profile of particularly stable intensity and optimum control, and hence repeatable pulse by pulse, even in the very long term.

5 Again advantageously, the described apparatus achieves optimal performance with an extremely limited total energy consumption due to the use of the laser diodes.

Advantageously, the described welding apparatus uses semiconductor laser diodes and a completely solid-state heat dissipation system and heat transfer  
10 against the ambient air, with a large reduction in the overall size and a large increase in efficiency and reliability.

As an example of these advantages in terms of energy consumption and heat dissipation, a welding apparatus such as the apparatus described is able to microweld gold chain rings made of gold wire of diameter 0.2 mm using less  
15 than one third the energy required by a lamp pumping apparatus constructed in accordance with the state of the art: this is so because the energy of a lamp-pumped welding apparatus is focused on an area or spot larger than the dimensions of the ring to be welded: Comparing the dissipated energy for the same spot weld:

20 - for the apparatus of the invention, 1 joule deposited on the workpiece to be welded requires 4 electrical joules supplied to the laser diodes: 2 joules are dissipated by the diodes, 1 joule is lost in the laser medium and is finally dissipated as heat; the total to be dissipated is about 3 joules;

- for the lamp welding apparatus, 3 joules supplied to the workpiece to be  
25 welded require at least 75-100 electrical joules at the lamp, of which 72-97 joules are dissipated in the form of heat. The energy consumption, which is transformed directly into a heat load to be dissipated, is in this example of application between 25 and 30 times higher for the lamp-pumped system.

It is hence apparent that, advantageously, this enables a liquid cooling system  
30 to be dispensed with, and moreover the much lower energy consumption enables the welding apparatus of the invention to be contained within a much smaller space. In this respect, the welding apparatus of the invention can be completely contained within a volume of about 6 litres, compared with the approximately 100 litres required for the most compact lamp-pumped systems.

35 Numerous modifications can clearly be made by an expert of the art to the

laser spot welding apparatus and the relative pumping method described by way of example, but without deviating from the principles of novelty contained in the inventive idea, it being also clear that in its practical implementation the forms of the illustrated details can be different, and can be replaced by

5 technically equivalent elements.

## CLAIMS

1. A laser spot welding apparatus of the type which generates a pulsed laser beam, comprising a pumping source (14) arranged to generate a pulsed pumping beam (13) for a resonant cavity (12) comprising an active means (11),  
5 characterised in that said pumping source (14) comprises a solid-state laser diode assembly.
2. A welding apparatus as claimed in claim 1, characterised in that said solid-state laser diode assembly (14) feeds said pumping beam (13) into the resonant cavity (12) in accordance with a longitudinal pumping scheme.
- 10 3. A welding apparatus as claimed in claim 1, characterised in that said solid-state laser diode assembly (14) feeds said pumping beam (13) into the resonant cavity (12) in accordance with a scheme of lateral pumping of the active means.
4. A welding apparatus as claimed in claim 2 or 3, characterised by  
15 comprising means (25, 27) for operating feedback control of the temporal pulse intensity profile.
5. A welding apparatus as claimed in claim 4, characterised in that said means (25, 27) for operating feedback control of the temporal pulse intensity profile comprise a photodiode (25) for measuring the power of the laser beam  
20 (17) and an electronic circuit (25) for feedback controlling a circuit (18) powering the diode assembly (14).
6. A welding apparatus as claimed in at least one of the preceding claims, characterised by comprising an optical focusing system (29, 30, 31) for positioning a focal point (22) for the welding.
- 25 7. A welding apparatus as claimed in claim 6, characterised in that said optical focusing system (29, 30, 31) comprises mirrors (29 and 30) positioned in the optical path of the laser beam (17) and rotatable about an axis to move the focal point (22) within a horizontal plane, and further comprises a focusing lens (31) possibly translatable in order to translate the focal point (22)  
30 vertically.
8. A welding apparatus as claimed in at least one of the preceding claims, characterised by comprising downstream of said resonant cavity (11) an optical fibre (19) and optical coupling means (21) for transmitting the pulses of the laser beam (17).
- 35 9. A welding apparatus as claimed in at least one of the preceding claims,

characterised by comprising aiming means (34, 35, 36) for the precise positioning of the workpiece (23) to be welded or of the focal point (22).

10. A welding apparatus as claimed in at least one of the preceding claims, characterised by comprising a solid-state cooling system.

5 11. A welding apparatus as claimed in at least one of the preceding claims, characterised by comprising a system of cooling by heat transfer to the environment, without liquid coolant.

12. A welding apparatus as claimed in claim 10 or 11, characterised in that said cooling system is associated with the laser diode assembly (14).

10 13. A welding apparatus as claimed in at least one of the preceding claims, characterised by comprising a micropositioning system (24) for workpieces (23) to be welded.

14. A welding apparatus as claimed in at least one of the preceding claims, characterised in that said active medium (12) comprises one of the following  
15 crystals: Nd:YVO<sub>4</sub>; Nd:GdVO<sub>4</sub>; and Nd:YLF.

15. A pumping method for a laser spot welding apparatus, of the type involving the following operations:

- generating a pumping beam (13) by activating a pumping source (14) with current pulses (18);
  - 20 - feeding the generated pumping beam (13) to an active medium (12) located in a resonant cavity (11), to obtain a pulsed laser beam (17);
  - conveying and focusing said laser beam (17) generated by said resonant cavity (11) onto a workpiece (23) to be welded
- characterised by

25 generating said pumping beam (13) by activating with current pulses (18) a solid-state laser diode assembly (14).

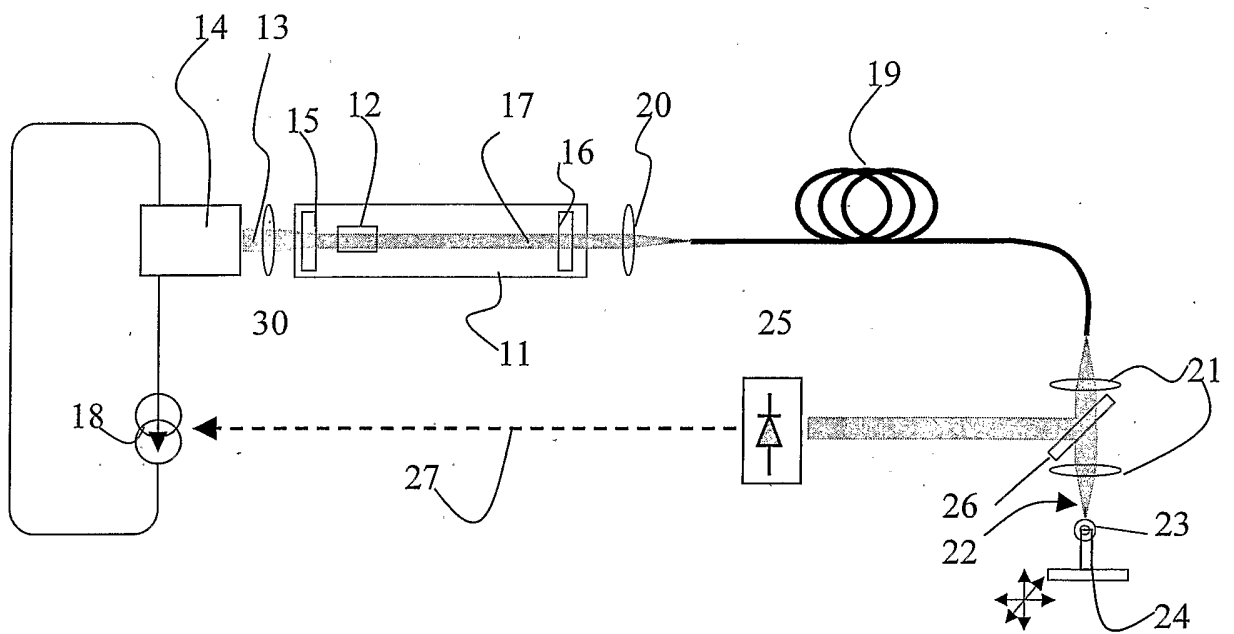
16. A pumping method as claimed in claim 14, characterised by also comprising the following operations:

- measuring (25) the power of the laser beam (17);
- 30 - feedback controlling (27) the temporal profile of said power of the laser beam (17) by operating on the current pulses (18) supplied to the laser diode assembly (14).

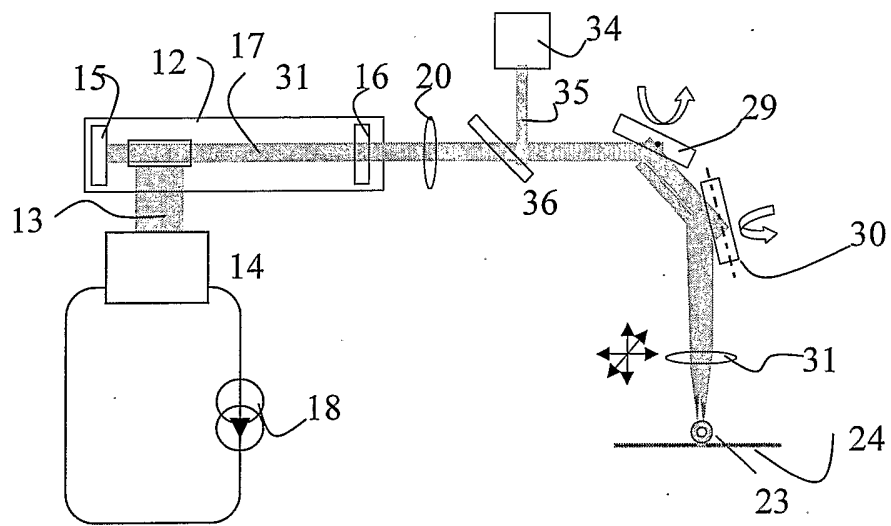
17. A method as claimed in claim 15, characterised in that said control operation (27) comprises compensating the power degradation of said laser  
35 beam (17).

18. A method of welding precious metal articles characterised by using an apparatus claimed in one or more of the preceding claims.

All substantially as described and illustrated and for the objects specified.



**FIG. 1**



**FIG. 2**