The Quantum Cascade Laser: Will it be the Mid and Far Infrared Laser of the Future?

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Abstract

Quantum Cascade lasers are small semiconductor lasers that emit light in the mid and far infrared portion of the spectrum. They have many advantages over other types of semiconductor lasers such as Lead Salt Diode lasers or Diode lasers. Some of the advantages include precise tuning from one wavelength to another, higher optical power, continuous wave operation and the ability to produce light in the terahertz range of the spectrum. This paper explores the advantages of Quantum Cascade lasers over other types of lasers that produce light in the mid infrared portion of the spectrum. During the exploration of these advantages, some applications of infrared light and Quantum Cascade lasers will be discussed.

Introduction

In 1917, Albert Einstein, a brilliant physicist, announced the possibility of producing light with certain key characteristics. It was not until the 1960s that the realization of this phenomenon was seen with the invention of the first laser. Since then, there have been continued breakthroughs in the development of new lasers that can perform tasks beyond previously established records. The Quantum Cascade laser, which was invented in 1994 and is currently being developed, is another example of a technological breakthrough that illustrates the ever-growing scientific innovations of man.

Quantum Cascade (QC) lasers are novel semiconductor devices that have a wide range of applications. Some of their applications include remote and point sensing of chemical vapors [1, 2] (such as Carbonyl sulfide, Carbon monoxide, Nitrogen monoxide etc), free space optical communication [3, 4], infrared counter measures, metal detection and astronomical applications. These applications are as a result of its ability to be tuned from one wavelength (a single color of light) to another, and the fact that it emits light in the mid and far infrared portion of the spectrum (these wave lengths are between 3.5 -24 micrometers and between 57 - 150 micrometers, respectively). This part of the spectrum is not visible to the human eyes. Figure 1 shows the location of the infrared portion of the spectrum compared to the visible portion of the spectrum. In addition, QC lasers are small compared to other lasers that produce light in that region of the spectrum. Nevertheless, there are other contending lasers such as lead salt diode lasers that emit light in that portion of the spectrum and also have a wide range of applications. In this paper, Quantum Cascade lasers (QC) will be compared to Lead Salt Diode (LSD) lasers or Diode lasers. In making this comparison, a brief overview of the properties of laser light will be given. Second, the importance of the mid and far infrared region of the spectrum will be discussed. And third, the characteristics of QC lasers which make them unique as opposed to LSD lasers will be explained.

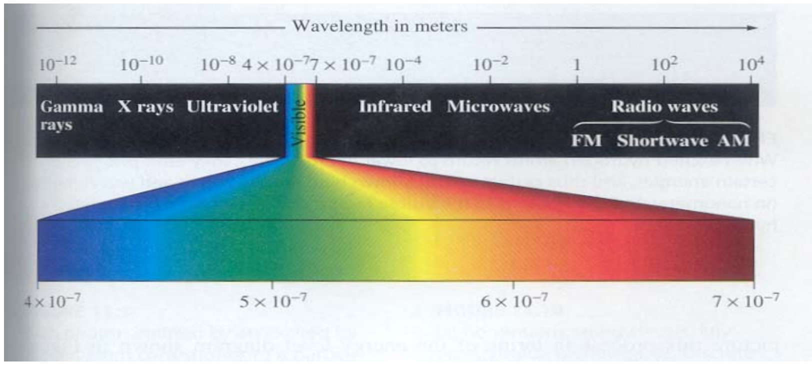

Figure 1: This picture shows the infrared portion of the spectrum with respect to the visible portion of the spectrum. The far infrared or terahertz wavelengths are close to the microwave wavelengths (Picture from Teacher Background Information website) [6].

The Meaning of the Word LASER

Many people have thought of the word "laser" as a base word, but it is actually an acronym, which stands for Light Amplification by Stimulated Emission of Radiation. This acronym comes from the principle by which laser light is produced. That is, in general, the simplistic way by which laser light is produced is as a result of electrons being excited from a lower energy level of an atom into a higher one (either by an electric field or intense light pulses). After some time, the electrons fall back to a lower energy level giving off radiation in the form of light, which possesses certain key characteristics. One characteristic of laser light is that it must be monochromatic, which means that it must be of a single color or wavelength and not a mixture of two or more colors. Another characteristic of laser light is that it must be coherent, which means that the waves of light must be in phase with each other; and the last characteristic of laser light is that it must be directional, which means that laser light cannot diverge as it travels over a certain distance. Laser light must be straight.

There are many types of lasers that cause this phenomenon (electrons being stimulated to a higher energy level and falling back

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down to give off energy in the form of light with certain characteristics) to happen in different ways. Some of the various types of lasers include helium–neon gas laser, carbon dioxide gas lasers, and dye lasers. However, the problem is that all of these lasers are extremely big and they do not produce light in the mid and far infrared portion of the spectrum [7]. Yet, the mid and far infrared portion of the spectrum is extremely important because many gasses that people are interested in monitoring have their distinctive absorption features in this portion of the spectrum [9]. In the next section, I will shed some light on the importance of the infrared portion of the spectrum.

Applications of the Mid and Far Infrared Portion of the Spectrum

There are many important applications of the mid and far infrared portion of the spectrum. One application is as a result of the fact that most gasses of interest, such as carbon sulfide, carbon monoxide, nitrogen monoxide, carbonyl sulfide etc, have their absorption finger print features in this portion of the spectrum [8]; that is, each gas has their unique characteristic wavelength for which they can be tuned to, in order to sense them. It is like the loops on the human finger or the DNA strand of a human being for which everybody's own is unique. The importance and process by which the QC laser senses various gasses will be explained in a future paragraph since more research work has been done on this area of QC laser research and LSD laser research. In addition to trace gas sensing, the mid or far infrared portion of the spectrum is important because metal detection occurs in this portion of the spectrum (due to the fact that all bodies give off infrared light in the form of heat) [10]. Distant space objects also give off light in that portion of the spectrum. Hence this part of the spectrum is of significance to astronomers. This part of the spectrum is also important because it enables free space optical telecommunication. That is, a mid infrared laser could be used to send digital information from one building top to another through free space without the use of optical equipments such as optical fibers. There are many more important applications of the infrared portion of the spectrum. We therefore need small lasers that can produce light in the mid and far infrared portion of the spectrum.

With the invention of the lead salt diode laser (LSD laser) in the 1970's, there was a laser source that could produce light in the mid infrared portion of the spectrum. Nevertheless, due to the physics of LSD lasers, there are some shortcomings [11]. In the proceeding paragraphs, I will attempt to compare QC lasers to LSD lasers. Various comparison parameters will be used, such as the ability of a single laser to be tuned from one wavelength to the other (for the sensing of different gasses), their maximum optical power, and the maximum temperature under which they can operate in continuous wave mode. As I am discussing the above points, an explanation of the importance of laser tunability from one wavelength to the other will be given. In addition, a brief explanation of what continuous wave operation means will also be given. Since trace gas sensing at a higher operating temperature is one of the major strengths of QC lasers, the importance of trace gas sensing and how it is done will be discussed in the ensuing paragraph.

Importance of Gas Sensing

As stated previously, an important application of mid infrared laser light is trace gas sensing. This is because many poisonous gasses of interest have their finger print absorption features in this part of the spectrum. There are direct medical applications of trace gas sensing with QC lasers. An example is in patients suffering from a certain type of liver illness or acute lung rejection, because they give off carbonyl sulfide in trace quantities (in the part per billion per volume). QC lasers were reported that have the potential to measure these trace quantities of carbonyl sulfide at room temperature [2] This will eliminate the possibility of performing surgery or using more expensive or complex tests in diagnosing such liver illnesses or acute lung rejection. LSD lasers might be able to perform this task, but they will need cryogenic cooling (typically less than 200 degrees Kelvin). This basically means that one would have to carry cryogenic liquid tanks wherever carbonyl sulfide is to be detected. It will not be convenient. Instead, there is a demand for small compact systems that could be hand held, and carried from one place to the other for trace gas sensing. QC lasers offer that advantage even though they are still in their developmental stage. Furthermore, QC lasers have been used to sense byproducts of fossil burning fuels at much higher temperatures than LSD lasers. These gasses are of interest because they are an important factor in pollution monitoring and in determining the emission of green house gasses that cause global warming. Some of the byproducts that QC lasers are used to measure include methane, carbon monoxide, carbon dioxide, etc [1]. However, as stated before, lead salt diode lasers have to be cooled to below 120 degrees Kelvin for good measurements [7]. It is important to have

compact lasers that could operate at higher temperatures so that they could be used commercially for the sensing of various air pollutants. This will aid scientists and government officials in their various endeavors, such as monitoring traffic emission pipeline leak detection, and in the mapping of atmospheric chemistry [20].

Advantages of Quantum Cascade (QC) Lasers

a) A single laser can be tuned from one wavelength to the other externally.

The sensing of these various gasses is done by the laser being able to be tuned from one wavelength to the other in a precise or smooth manner. When a laser is used to sense a particular gas, one wavelength is tuned precisely to match the finger print wavelength for which the various molecules of the gas are vibrating in. The second wavelength serves as a calibration in order to determine whether the first wavelength was tuned correctly. A single QC laser offers the tremendous advantage of being able to be tuned from one wavelength to the other in a precise manner [9]. This is because in QC lasers the wavelength is determined by such external factors as current flowing into the laser and the external temperature. By changing the direction of the electrical current flowing into the laser, the wavelength could be increased or decreased [5, 12]. Furthermore, the wavelength could be increased by increasing the external temperature for which the laser is operating and vice versa [1, 13]. A single LSD laser does not offer the advantage of fine-tuning from one wavelength to the other externally. This could only be explained from the physics of LSD lasers. Hence, in order for LSD lasers to be used for trace gas sensing, lasers of different wavelengths would probably have to be stacked on top of each other with the hope that one of the laser's wavelengths would match the characteristic wavelength of the gas molecules. Nevertheless, there will always be gaps for which the system of stacked lasers would not be able to detect some gasses of interest. Therefore, QC lasers offer a better advantage over LSD lasers in spectroscopic applications such as trace gas sensing.

b) Quantum Cascade Lasers have higher optical power than other types of mid and far infrared lasers.

QC lasers offer another advantage. They have a higher optical power than LSD lasers which produce light in the mid infrared portion of the spectrum. The Industrial Physicist magazine by the American

Institute of Physics reported that some QC lasers with the same wavelength as Diode lasers have over 1,000 times the power of Diode lasers [3]. The high power ability of the QC laser can be attributed to the particular way in which the laser structure was engineered. It is important to have high power lasers because different laser applications have different power needs. For example, the sensing of certain types of gasses (such as methane) needs higher optical power than the sensing of other types of gasses. For this reason, Diode lasers have limited sensitivity to gasses such as methane because their optical power is low [7]. Therefore, by having high power lasers that produce light in the mid and far infrared portion of the spectrum, there will be more potential applications.

c) Quantum Cascade Lasers can operate in continuous wave mode at room temperature.

Furthermore, there is a demand for mid and far infrared laser systems that operate in continuous wave mode at room temperature. This is because these types of laser systems would be able to perform tasks such as trace gas sensing or free space optical communication better than pulsed lasers. To understand what it means for a laser to be operating in continuous wave mode or pulsed mode, a concept known as duty cycle would have to be introduced. One could think of the duty cycle as the intensity of electrical load that a particular circuit can take. The maximum duty cycle is continuous wave mode, and pulsed mode is obtained at lower duty cycles. Knowledge of the duty cycles of an electrical circuit enables engineers to design power packs for various lasers. QC lasers were demonstrated to operate in continuous wave mode at room temperature [1, 13]. The ability of QC lasers to operate in continuous wave mode is another factor that aids in its better gas sensing. Since the development of QC lasers has progressed to this level of advancement, there is the possibility that QC lasers will soon be available for broad commercial use for the general public. On the other hand, the maximum temperature for which LSD lasers were demonstrated to operate on continuous wave mode is 203 degrees Kelvin [14]. As stated previously, a laser system composed of LSD lasers would need cryogenic cooling in order to operate on continuous wave mode. This is not feasible for commercial applications. It would be like attaching a tank of liquid nitrogen to the laser in your CD player in order to cool it whenever it heats up!

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d) Quantum Cascade Lasers are small compared to other types of mid and far infrared lasers.

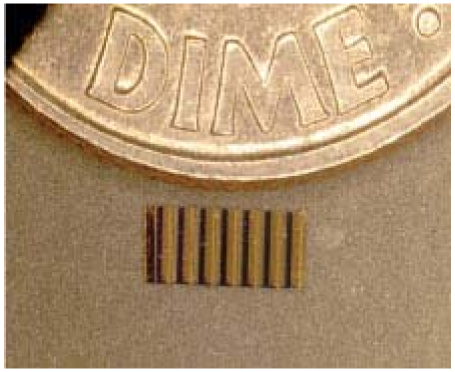

Figure 2: Shows an array of 7 Quantum Cascade lasers on a chip with a dime close to it. The actual lasers are in the vertical ridges. They are protected by other semiconductor materials on top to prevent damage (Courtesy of Professor Claire Gmachl, Department of Electrical Engineering, Princeton University) [15].

Additionally, the QC laser offers an advantage in its size, and it will eventually become cheap to the general public after its full development. QC lasers are typically 3 millimeters in length and a fraction of a hair strand in thickness. See Figure 2 for an array of QC lasers on a chip compared to the size of a dime [15]. The cooling equipment required for the QC laser can be made as small as a few cubic inches [3]. This small and compact size offers several advantages, especially for commercial use. A small compact QC laser system could be made in such a way that a person could carry it from one place to the other, and perform multiple tasks with it. In comparison, Diode lasers are much bigger than QC lasers. LSD lasers are comparable in size to QC lasers, but after the full development of QC lasers they will become cheap and more reliable than LSD lasers [16]. This is because QC lasers are made from semiconductor materials. Semiconductor materials are cheap, and the cost of processing them is generally low. Hence, the general QC laser system, including the cost of the cooling equipment, will eventually become cheaper than LSD lasers. As seen from the previous paragraphs of the comparison of QC lasers with LSD or Diode lasers, it could be inferred that LSD lasers are relatively unreliable and have multiple shortcomings.

e) Quantum Cascade Lasers produce Laser light in the terahertz portion of the spectrum.

Finally, QC lasers have a unique property that no other type of semiconductor laser can perform, which is to produce laser light at the terahertz wavelength (also known as the far infrared portion of the spectrum). This portion of the spectrum is characterized by very high wavelengths, typically between 87 micrometers and 150 micrometers. It is very hard to engineer a laser that will achieve these wavelengths [17]. An essential importance of these wavelengths results from the fact that metal detection occurs there. This is because metals have very good reflectivity at these wavelengths. An example of an important application of metal detection is in airport systems, or in a high-rise building to spot whether a person is carrying a metal object (such as a gun). These lasers could be focused on the person and hence the image of the metal object (or gun) will appear. This distinguishes QC lasers from all other types of lasers that produce light in the infrared portion of the spectrum.

Conclusion

The Quantum Cascade laser, which was invented in 1994 [5] at Bell Laboratories, holds great promise in the near future for many applications. It could be used for trace gas sensing of chemical vapors (which enables it to diagnose certain types of diseases), metal detection (which enables it to function as a counter terrorism tool), infrared counter measures (which enables it to detect missiles), and for free space optical communication. It could also be tuned from one wavelength to the other and operate in continuous wave mode at room temperature. This makes it more convenient for commercial use and enables it to better sense gasses. In addition to all the above attributes, the QC laser can operate at powers higher than Diode lasers and produce light at the terahertz wavelengths, a factor that distinguishes it from all other types of lasers. Considering all of the above facts, it is evident that the Quantum Cascade laser might be the mid and far infrared laser of the future. It might eventually render Lead Salt Diode lasers obsolete.

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