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Performance of atomic lines filters in laser tracking and communication

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ABSTRACT

An atomic line filter (ALF) is an advanced optical band-pass filter used for the filtering of electromagnetic radiation with precision, accuracy, and minimal signal strength loss. Atomic line filters work via the absorption or resonance line of atomic vapors and so may also be designated an atomic resonance filter (ARF). This paper will bring out the role of atomic line filters in the filtering of electromagnetic radiation in three context, absorption-re-emission (ALFs), faraday filters and voigt filters with their principles. Also in this paper we will look at how atomic line filters are most often used in LIDAR and other exercises in laser tracking and communication. With the superior filtering system of an ALF, a non-intensified CCD may be used with a continuous wave laser more efficiently. Atomic line filters with pass-bands of about 0.001 nm have been developed to improve the background rejection of conventionally filtered laser receivers.

INTRODUCTION

A technical definition of an atomic line filter is as an "ultra-narrow-band, large-acceptance-angle, isotropic optical filter". Ultra-narrow-band" defines the thin range of frequencies that an ALF may accept; an ALF generally has a pass-band of 0.001 nm. Atomic line filters also have wide acceptance angles (near 180°) which is another important characteristic of the devices; conventional dielectric filters based on the spacing of reflective or refractive layers change their effective spacing when light enters at an angle (Gelbwachs, el ta, 1977).

The predecessor of the atomic line filter was the infrared quantum counter, designed in the 1950s by Nicolaas Bloembergen. This was a quantum mechanical amplifier theorized by Joseph Weber to detect infrared radiation with very little noise, (Bloembergen, 1958). Zero spontaneous emission was already possible for X-ray and gamma ray amplifiers and Weber thought to bring this technology to the infrared spectrum. Bloembergen described such a device in detail and dubbed it the infrared quantum counter. (Gelbwachs, el ta 1977).The media of these devices were crystals with transition metal ion impurities, absorbing low-energy light and re-emitting it in the visible range. By the 1970s, atomic vapors were used in atomic vapor quantum counters for detection of infrared electromagnetic radiation, as they were found to be superior to the metallic salts and crystals that had been used. The principles hitherto employed in infrared amplification were put together into a passive sodium ALF. This design and those that immediately followed it were primitive and suffered from low quantum efficiency and slow response time (Goodwin, 1974).

As this was the original design for ALFs, many references use only the designation "atomic line filter" to describe specifically the absorption-re-emission construction. (Weber, and Marvin, 2003).

In 1977, Gelbwachs, Klein and Wessel created the first active atomic line filter. Faraday filters, developed sometime before 1978, were "a substantial improvement" over absorption-re-emission atomic line filters of the time (Gelbwachs, el ta, 1977). The Voigt filter, patented by James H. Menders and Eric J. Korevaar on August 26, 1992, was more advanced. Voigt filters were more compact and could be easily designed for use with a permanent magnet. By 1996, Faraday filters were being used for LIDAR. (Chen el ta, 1996). Atomic line filters are inherently very efficient filters, generally classified as "ultra-high-Q" as their *Q* factor is in the 10^5 to 10^6 range. This is partially because the, crossed polarizer's serve to block out background light with a rejection ratio better than 10^{-5}. The pass-band of a typical Faraday filter may be a few GHz. The total output of a Faraday filter may be around 50% of the total input light intensity. The light lost is reflected or absorbed by imperfect lenses, filters and windows. (Chen el ta, 1996).

The band-pass of an atomic line filter is usually equal to the Doppler profile of the vapour cell, the natural range of frequencies at which a vapour cell will be excited by a pure light source (Popescu el ta, 2005). The Doppler profile is the width of the spectrum of Doppler shifted radiation emitted by the vapour cell due to its thermal motion. This value is less for larger atoms at lower temperatures, a system considered more ideal. There are some circumstances where this is not the case, and it is desirable to make the width of the transition line larger than the Doppler profile. For instance, when tracking a quickly accelerating object, the band-pass of the ALF must include within it the maximum and minimum values for the reflected light (Fitzpatrick, and Richard. 2002).

MATERIALS AND METHODS

The accepted method for increasing the band-pass involves placing an inert gas in the vapour cell. This gas both widens the spectral line and increases the transmission rate of the filter. (Chen el ta 1996)

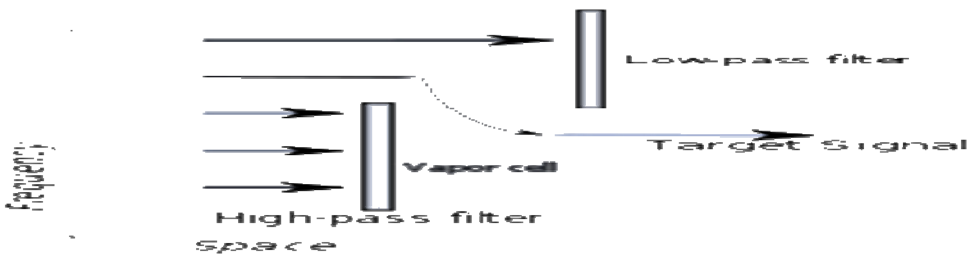

Figure 1: The diagram of vector graphic depicts an abstraction of the methodology of an absorption re-emission ALF.

However, only a narrowband may bypass two broadband filters and create a very precise and accurate filter. Here, a careful manipulation of the frequency of incoming light may be translated into a special translation (Popesc el ta, 2005). A similar strategy is employed in both Faraday and Voigt filters, though in these filters, the polarization of the light is shifted and not the frequency.

An absorption-re-emission atomic line filter absorbs the desired wavelength of light and emits light that bypasses broadband filters. In passive absorption-re-emission ALFs, a high-pass filter blocks all low-energy incoming light. The vapour cell absorbs the signal, which coincides with the vapour's thin absorption line, and the cell's atoms become excited. The vapour cell then re-emits the signal light by undergoing fluorescence at a lower frequency (Korevaar,1989). A low-pass filter blocks radiation above the frequency of the fluorescent light. In an active ALF, optical or electrical pumping is used for exciting these atoms so they absorb or emit light of different wavelengths (Fitzpatrick, and Richard 2002),. Hence for active ALFs, other systems of conventional filters may be needed.

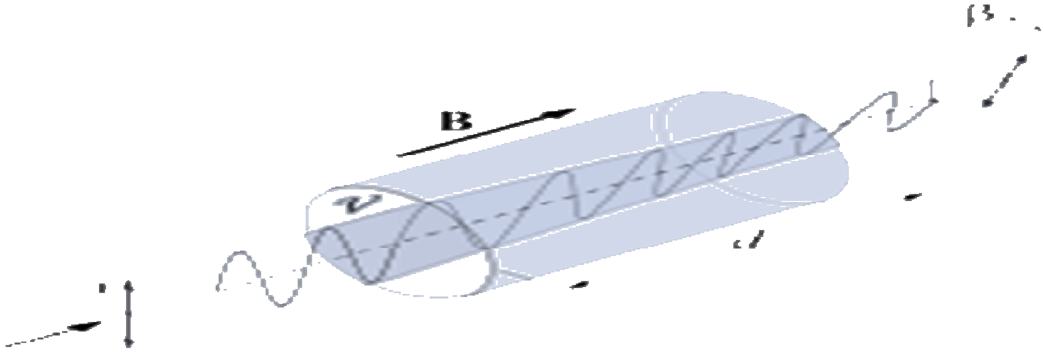

Figure 2: Polarization of light by a Faraday filter
(Taisuke, 1978)

A Faraday filter, magneto-optical filter, FADOF or EFADOF (Excited Faraday Dispersive Optical Filter) works by rotating the polarization of the light passing through the vapor cell. This rotation occurs near its atomic absorption lines by the Faraday Effect and anomalous dispersion. Only light at the resonant frequency of the vapor is rotated and the polarized plates block other electromagnetic radiation. This effect is related to and enhanced by the Zeeman Effect or the splitting of atomic absorption lines in the presence of the magnetic field. Light at the resonant frequency, of the vapor exits a FADOF (Faraday Dispersive Optical Filter) near its original strength but with an orthogonal polarization. Following the laws which govern the Faraday effect, the rotation of the targeted radiation is directly proportional to the strength of the magnetic field, the width of the vapor cell and the Verdet constant (which is dependent on the temperature of the cell, wavelength of the light and sometimes intensity of the field) of the vapor in the cell. This relationship is represented the following equation:

$$\beta = \mathcal{V}Bd \quad \text{--} \quad (1)$$

A Voigt filter is a Faraday filter with its magnetic field shifted to be perpendicular to the direction of the light and at 45° to the polarization of the polarized plates. In a Voigt filter, the vapor cell acts as a half wave plate, retarding one polarization by 180° per the Voigt effect

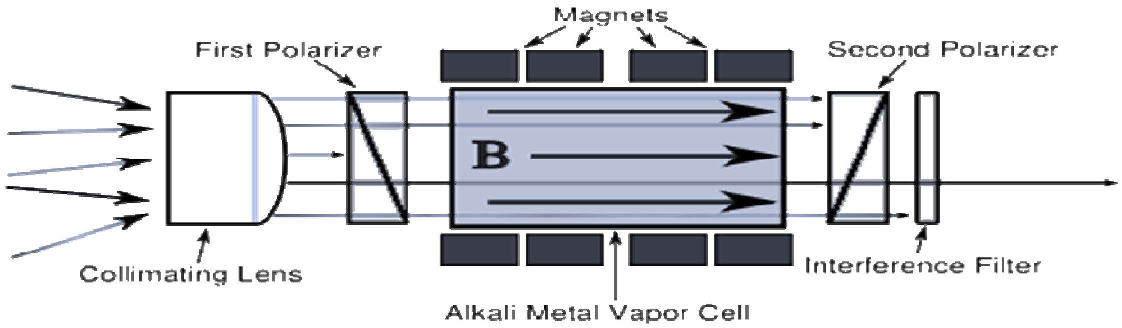

Figure 3: A diagram of the parts of a Faraday filter.
(James etal, 1992)

In a Voigt filter, the magnetic field would be rotated 90 degrees. Note that the two polarizer plates are perpendicular in direction of polarization. Preceding an atomic line filter may be a collimator, which straightens incident light rays for passing through the rest of the filter consistently; however, collimated light is not always necessary, the collimator, a high-pass filter blocks almost half of the incoming light (that of too long a wavelength). In Faraday and Voigt filters, the first polarizing plate is used here to block light. The next component in an atomic line filter is the vapor cell; this is common to all atomic line filters. It either absorbs and re-emits the incident light, or rotates its polarization by the Faraday or Voigt effect. Following the vapor cell is a low-pass filter, designed to block all of the light that the first filter did not, except the designated frequency of light which came from the fluorescence. In Faraday and Voigt filters, a second polarizing plate is used here.

Other systems may be used in conjunction with the rest of an atomic line filter for practicality. For instance, the polarizer's used in the actual Faraday filter don't block most radiation, "because this polarizer's only work over a limited wavelength region, a broad band interference filter is used in conjunction with the Faraday filter". The pass-band of the interference filter may be 200 times that of the actual filter. Photomultiplier tubes (PMTs), too, are often used for increasing the intensity of the output signal to a usable level. Avalanche photomultipliers, which are more efficient, may be used instead of a PMT. While every implementation of each kind of ALF is different, the vapor cell in each is relatively similar. The thermodynamic properties of vapor cells in filters are carefully controlled because they determine important qualities of the filter, for instance the necessary strength of the magnetic field. Light is let into and out of this vapor chamber by way of two low-reflection windows made of a material such as magnesium fluoride. The other sides of the cell may be of any opaque material, though generally a heat-resistant metal or ceramic is used as the vapor is usually kept at temperatures upwards of 100 °C.

Most ALF vapor cells use alkali metals because of their high vapor pressures; many alkali metals also have absorption lines and resonance in the desired spectra. Common vapor cell materials are sodium, potassium and caesium. Note that non-metallic vapors such as neon may be used. As the early quantum counters used solid state metal ions in crystals, it is conceivable that such a medium could be used in the ALFs of today. This is presumably not done because of the superiority of atomic vapors in this capacity.

Atomic line filters are most often used in LIDAR and other exercises in laser tracking and detection, for their ability to filter daylight and effectively discern weak, narrowband signals; however, they may be used for filtering out the earth's thermal background, measuring the efficiencies of antibiotics and general filtering applications

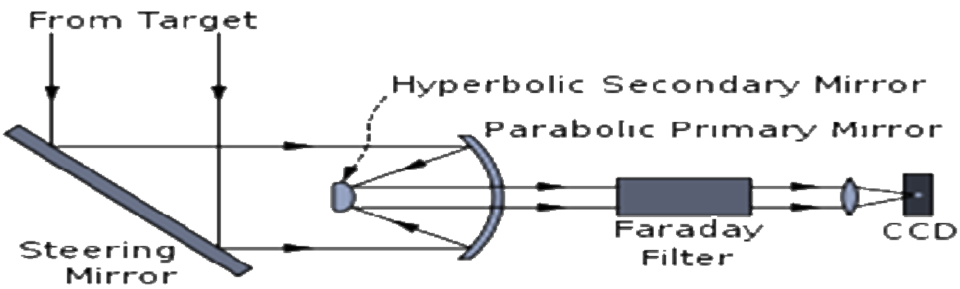

Figure 4: Diagram of the receiver end of a laser tracking system
(Popescu, 2005).

DISCUSSION AND CONCLUSION

Laser tracking and communication

Without an atomic line filter, laser tracking and communication may be difficult. Usually, intensified charge-coupled device cameras must be used in conjunction with simple dielectric optical filters (e.g. interference filters) to detect laser emissions at a distance (Gelbwachs el ta,1977). Intensified CCDs are inefficient and necessitate the use of a pulsed laser transmission within the visible spectrum. With the superior filtering system of an ALF, a non-intensified CCD (Charge-Couple Device) may be used with a continuous wave laser more efficiently. "Atomic line filters with pass-bands of about 0.001 nm have been developed to improve the background rejection of conventionally filtered laser receivers". The total energy consumption of the latter system is "30 to 35 times less" than that of the former, so space-based, underwater and agile laser communications with ALFs have been proposed and developed.

LIDAR (*Laser Imaging Detection and Ranging)* comprises firing lasers at relevant portions of the atmosphere where light is backscattered. By analyzing the reflected laser beam for Doppler shifts, wind speeds and wind directions in the target region may be calculated. However, without the ability to effectively track weak laser signals, collection of atmospheric data would be relegated to times of day where the sun's electromagnetic emissions did not drown out the laser's signal (Höffner, and Fricke-Begemann, 2005). The addition of an atomic line filter to the LIDAR equipment effectively filters interference to the laser's signal to the point where LIDAR data can be collected at any time of the day. For the past decade, Faraday filters have been used to do this. Consequently, scientists know significantly more today about the Earth’s middle atmosphere than they did before the advent of the FADOF

Recommendation

For all of their efficiency, atomic line filters are not perfect; there are many sources of error, or “noise”, in a given system. These are manifest as electromagnetic radiation independent of the working processes of the filter and the intensity of the signal light. One source of error is the thermal radiation of and within the ALF itself. Some thermal radiation comes directly from the filter and happens to be within the band pass of the second broad band filter. More noise is created if the filter is designed for output in the infrared range, as most of the thermal radiation would be in that spectrum. Therefore careful should be observed to minimize these errors.

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