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High power fiber lasers and amplifiers/Lasers et amplificateurs à fibre de puissance

# Laser source requirements for coherent lidars based on fiber technology

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**Abstract**

Fiber lasers are becoming new effective sources for coherent lidars, thanks to their spatial and spectral qualities. Allowing operation in continuous, modulated and pulsed modes, their increasing power at eyesafe wavelengths is well suited to anemometry, velocimetry, vibrometry or laser imagery. Requested laser qualities are discussed, concerning wavelength, power, pulse duration and frequency, beam shape and spectral width, and compared to existing fiber source parameters. ***To cite this article: J.-P. Cariou et al., C. R. Physique 7 (2006).***



**Résumé**

**Spécifications des sources laser pour des lidars cohérents à technologie fibrée.** Les lasers à fibre apparaissent comme de nouvelles sources adaptées aux applications de lidars cohérents, grâce à leurs qualités spatiales et spectrales. Pouvant fonctionner en mode continu, modulé ou impulsionnel, leur puissance croissante en fait des sources d'intérêt pour des applications d'anémométrie, de vélocimétrie, de vibrométrie ou d'imagerie laser. Les qualités requises pour ces sources sont ici discutées, concernant la longueur d'onde, la puissance, la durée et la cadence des impulsions, le profil de faisceau et la largeur spectrale. Les lasers fibrés peuvent avantageusement être configurés en MOPA (Maître Oscillateur et Amplificateur de Puissance) permettant d'optimiser séparément la qualité spectrale, la modulation et la puissance de sortie. Le choix de longueur d'onde prend en compte la transmission atmosphérique, le rapport porteuse sur bruit et la sécurité oculaire. Le choix de lasers fibrés Er–Yb dans la bande 1,5 µm s'avère particulièrement adapté. Les puissances requises pour des applications opérationnelles sont de l'ordre de 10 W moyens pour une énergie de 1 mJ par impulsion. La qualité spatiale exigée correspond à un paramètre $M^2$ inférieur à 1,7. Du point de vue spectral, une finesse spectrale de l'ordre de 10 kHz en continu et 100 kHz en impulsionnel couvre les besoins. La réalisation de sources fiables demande cependant encore des efforts technologiques sur les fibres et les coupleurs pour concilier qualité et puissance. ***Pour citer cet article : J.-P. Cariou et al., C. R. Physique 7 (2006).***



*Keywords:* Fiber lasers; Fiber amplifiers; Coherent lidars

*Mots-clés :* Lasers à fibre ; Amplificateurs à fibres ; Lidars cohérents

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## 1. Introduction

Laser radars constitute a direct extension of radar techniques to optical wavelengths (0.2–12 µm). Whether they are called lidars (light detection and ranging) or ladar (laser detection and ranging), they operate on the same basic principles as microwave radars [1]. Because they use much shorter wavelengths (i.e., higher frequencies), lidars are capable of higher accuracy and resolution than microwave radars. However, atmospheric propagation limits their performance. Advances in lidar have closely followed advances in laser technology since the invention of the laser. Rather than supplanting microwave radar, laser radar opens up new capabilities that make use of the large shift in wavelength, including military tactical range and velocity systems, aircraft navigation and remote atmospheric sensing. The wide flexibility is given both by the used technique (continuous wave, pulsed, focused, collimated) and by the different available wavelengths and energies.

For 10 years, fiber lasers have been offering a new, effective and high visibility technology to the lidar community, allowing new instruments to be designed. The advent of the double clad fiber, along with advances in semiconductor pump diode sources, have allowed rapid power scaling of both pulsed and CW fiber sources. The different articles of this issue provide details on power scaling achievements and future directions [2,3]. The unique capabilities of fiber sources, coupled with significant commercial and academic progress in implementation, have driven fiber technology to enter active remote sensing markets as signal sources and amplification stages for direct detection lidars and coherent lidars as well [4] .

## 2. General lidar requirements

Coherent lidars use heterodyne detection by mixing (i.e., interfering) the laser light scattered from a remote target with a reference local coherent laser oscillator. This technique offers high sensitivity as well as providing detailed phase and velocity information. Heterodyne detection outputs an electrical RF beat note, proving information on the complex amplitude of the signal field. Reflectivity is calculated from signal strength, range from time of flight and speed from frequency or phase shift. Even the polarization state can be derived from the lidar signal, giving information on the target composition.

Coherent lidars need both a low power continuous wave (CW) laser as a local oscillator (LO), and a main powerful CW or pulsed laser for transmitting energy to the target. These lasers need to have a stable frequency relationship to ensure narrow band detection. Often, part of the LO is used as a seeder for the main laser. In fibered architectures, the best architecture comprises a CW low power as LO which is also used as master oscillator of a fibered power amplifier in single path. Fibered amplifiers have a very large bandwidth (>3 THz at 1550 nm) and large gain, allowing various waveforms to be amplified (CW, modulated, pulsed).

To design a lidar, the above factors have to be considered. To gather all requested qualities and separate the functions, a MOPA configuration (Master Oscillator Power Amplifier) is put forward. The MOPA (Fig. 1) includes an oscillator, delivering a CW polarized low power single mode beam, having requested spectral linewidth and stabil-

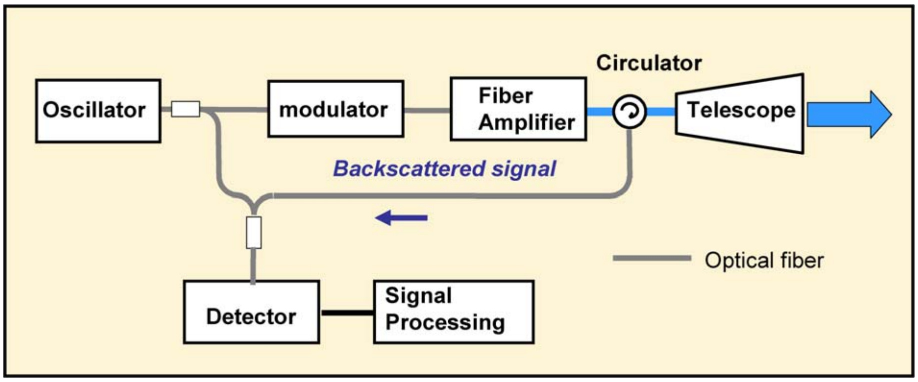


Fig. 1. Coherent fiber lidar block diagram.

Fig. 1. Schéma bloc d'un lidar fibré cohérent.

ity, a modulator that performs the pulse shape and the spectral shift or chirp, and then one or several cascaded fiber amplifiers. Using MOPA lasers, the spectral content, the waveform and the power level can be optimized in three independent components: as a result, fiber lasers are suitable sources for coherent lidars. Laser specifications are demanding as far as range and resolution are concerned.

## 3. Wavelength specifications

Atmospheric propagation, Carrier-to-Noise Ratio (CNR), laser eye safety, angular and velocity resolution have to be analyzed in different spectral bands, and selected wavelengths compared to fiber technology availability.

### *3.1. Atmospheric propagation*

Laser lines must be chosen in atmospheric windows. In the near infrared band (NIR or band I, 0.8–2.5 μm), spectral absorption is mainly due to water vapour and $CO_2$. Fig. 2 points out absorption lines in band I, where commercial Yb, Er–Yb and Tm silica fiber lasers and amplifiers can be found.

Maximum transmission in the different spectral bands depends on aerosol concentration and content. Aerosol transmission $T_{\mathrm{atm}}$ rises slowly with wavelength and favours large wavelengths: $T_{\mathrm{atm}} = \mathrm{e}^{-\alpha(\lambda)Z}$, with $\alpha(\lambda) = \alpha_{(\lambda=1\ \mu\mathrm{m})}.\lambda^{3/2}_{(\mu\mathrm{m})}$ (see Fig. 2). However, the aerosol backscattering coefficient $\beta_\pi$ is proportional to $\alpha$ and favours short wavelengths. For long range hard target lidars, 2 μm spectral range is a good choice. For atmospheric medium range lidars, atmospheric influence is similar between 1 and 2 μm.

Some interesting fiber laser wavelengths benefit from a good transmission in the near infrared spectral band: Ytterbium lasers (1.0–1.06 μm), Erbium lasers (1.48–1.62 μm) and Thulium lasers (1.8–2.1 μm) [5]. Gain profiles of the different interesting rare earths in Silica are also given on Fig. 2. However, in the 2 μm spectral band the laser must be tuned very accurately between absorption lines and must remain stable (Fig. 3(b)).

Critical lidar components are available around 1.5 μm because of telecom applications. High bandwidth detectors, couplers, circulators, acousto-optic or electro-optic modulators, single mode fibers are widely developed around the world. At other wavelengths, 1 and 2 μm, custom components can be developed but remain expensive.

At longer wavelengths (band II, 3–5.5 μm), some fiber lasers have been developed in the recent years [6,7]. They use Erbium, Ytterbium or Praseodymium in fluoride fibers. Their power and spectral quality are, however, today too low for coherent lidar applications.

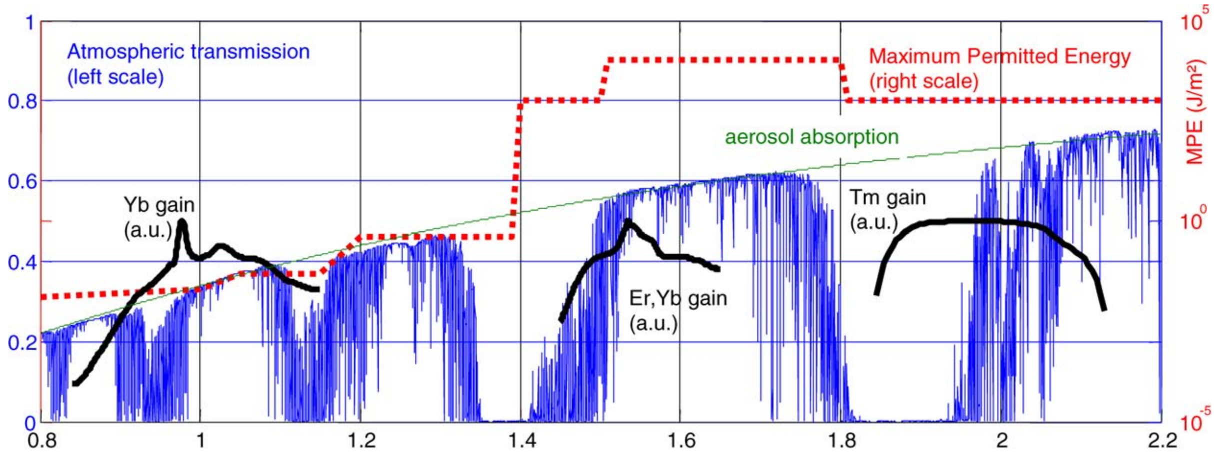


Fig. 2. Blue: Atmospheric transmission between 0.8 and 2.2 μm (European climate—6 km propagation from ground level to $h = 1000$ m; Green: aerosol absorption ($\alpha = 0.18\ \mathrm{km}^{-1}$ at $\lambda = 1$ μm). Black: Relative laser Gain in Yb, Er–Yb and Tm short length silica fiber lasers. Red: Maximum Permitted Energy for 100 ns pulse (log scale).

Fig. 2. Bleu : Transmission atmosphérique entre 0,8 et 2,2 μm (climat européen—6 km de propagation depuis le sol jusqu'à $h = 1000$ m ; Vert : absorption des aérosols ($\alpha = 0{,}18\ \mathrm{km}^{-1}$ à $\lambda = 1$ μm). Noir : gain relatif des lasers à fibre silice courte dopée Yb, Er–Yb et Tm. Rouge : Energie Maximale Permise pour des impulsions de 100 ns (échelle log).

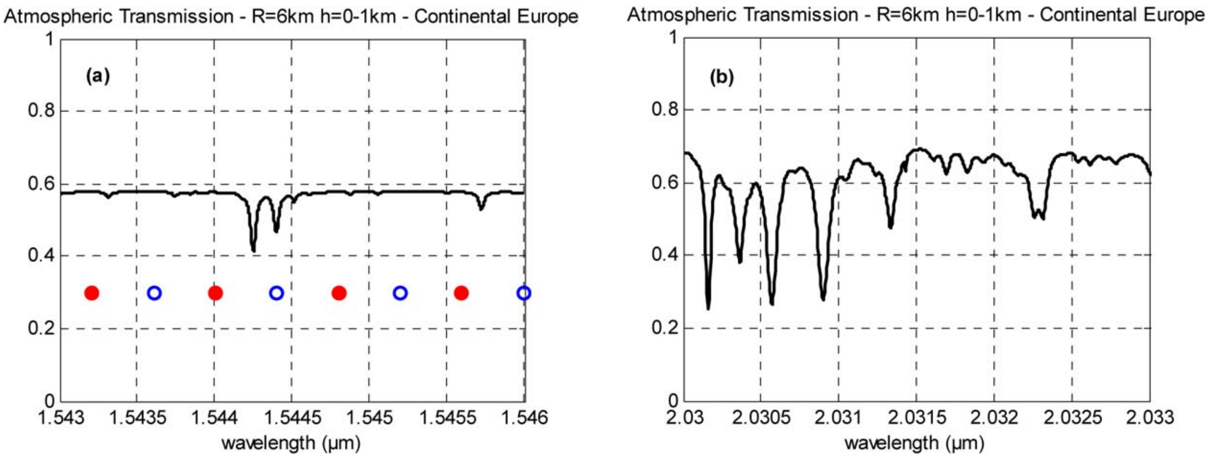


Fig. 3. (a) Atmospheric transmission around 1545 nm, and corresponding ITU 100 GHz grid in blue (open circles), with 50 GHz offset in red (full circles). (b) Atmospheric transmission around 2031 nm.

Fig. 3. (a) Transmission atmosphérique autour de 1545 nm, grille ITU 100 GHz correspondante en bleu (cercles ouverts), avec offset de 50 GHz en rouge (cercles pleins). (b) Transmission atmosphérique autour de 2031 nm.

### 3.2. *Carrier-to-Noise Ratio*

General lidar equation gives the CNR, i.e., the ratio between the signal power and the noise power. It informs on the ability of the lidar to detect low level signals in noise.

$$\mathrm{CNR} = \frac{P_s}{P_n}, \qquad P_s = \frac{\eta P_e \Re A_r \mathrm{e}^{-2\alpha Z}}{Z^2}, \qquad P_n = \frac{hcB}{\lambda} \tag{1}$$

with $P_s$: signal power, $P_n$: noise power, $\eta = T\eta_h\eta_q$: lidar efficiency ($T$: system transmission, $\eta_h$: heterodyne efficiency, $\eta_q$: quantum detector efficiency), $P_e$: emitted power (W), $\Re$: target reflectivity ($\mathrm{sr}^{-1}$), $\lambda$: laser wavelength (m), $\alpha$: atmospheric extinction coefficient ($\mathrm{m}^{-1}$), $A_r$: collection optics area ($\mathrm{m}^2$), $Z$: target range (m), $h$: Planck's constant. The main assumptions are: Gaussian beams, large area targets and quantum noise limited detection.

Most of the terms in the CNR equation favour long wavelengths:

- $B$ is proportional to $\lambda^{-1}$ in CW lidars, since Doppler frequency shifts and dispersion $\Delta f_d$ are related to radial velocity shifts $V_r$ by: $\Delta f_d = 2\Delta V_r/\lambda$. So, $P_n$ is proportional to $\lambda^{-2}$. For pulsed lidars, $B$ is often limited by the pulse length, and so $P_n$ is proportional to $\lambda^{-1}$.
- Heterodyne efficiency $\eta_h$ can be affected by atmospheric turbulence for large apertures and/or long ranges; long wavelength are less sensitive than short ones.
- Atmospheric aerosol transmission is better at long wavelengths (Fig. 2).

The only term that favours short wavelengths is the target reflectivity $\Re$ (see Section 3.1). However, angular and velocity resolutions are on the opposite proportional to $\lambda$, and long range high accuracy Doppler measurements may need the shortest possible wavelengths to insure a laser spot smaller than the target.

### 3.3. *Eye-safety*

Eye safety may be an issue for atmospheric lidars. Above 1.4 μm, the maximum permitted exposure (MPE) is 3 orders of magnitude higher than for shorter wavelengths, as shown on Fig. 2 and an eye-safe operation is possible even with multi-watt lasers [8]. Following the standards, the Ytterbium laser is considered as a dangerous laser even at long range operation while Erbium and Thulium lasers are safe lasers.

### 3.4. Er–Yb fiber laser wavelength specifications

Because Yb fiber lasers are not eye-safe and Tm fiber lasers are not as mature as Er–Yb fiber lasers [9], we focus now our requirements on Er–Yb lasers. Many specifications are, however, suitable for other bands.

Erbium–Ytterbium codoped fibers have 3 different gain peaks (1535, 1545, 1565 nm) depending on the average Erbium inversion in the used fiber. The width of each window is about 5 nm.The larger is the inversion, the larger is the pump power required. Amplification at 1565 nm thus requests a lower pump power than at 1535 nm. However, because the gain is lower, the amplifier should be 3 times longer and thus this lowers the stimulated Brillouin scattering (SBS) threshold, limiting the peak power [10]. In the three sub-bands, thanks to laser tunability, spectral atmospheric windows can be found with good transmission.

Fig. 3 highlights the transmission around 1545 nm , and also shows the ITU grid in this region. The ITU grid (100 GHz steps) corresponds to telecom standard WDM lines. Commercial components (oscillators, filters) are developed specially at these wavelengths, reducing the cost of lidar development.

Available oscillators in this spectral band are DFB diodes and fiber lasers. Laser diodes are more powerful than fiber lasers and offer better wavelength tunability with temperature: typically 0.09 nm/° for a laser diode and 0.01 nm/° for a fiber laser.

## 4. Energy, power, pulse duration and pulse rate

Two systems are investigated: a pulsed Doppler wind lidar for atmospheric remote sensing, and a continuous wave Doppler lidar for hard target velocimetry.

### 4.1. Pulsed wind lidar

Targets are natural aerosols (dust or water particles). The target reflectivity is then: $\Re = \beta_\pi \frac{c\tau}{2}$, with $\tau$: pulse length (s), $\beta_\pi$: atmospheric backscattering coefficient ($\mathrm{m^{-1}\,sr^{-1}}$). $\beta_\pi$ varies from $10^{-6}\ \mathrm{m^{-1}\,sr^{-1}}$ at ground level to $10^{-10}\ \mathrm{m^{-1}\,sr^{-1}}$ at 10 km altitude. For a pulsed lidar, the power budget equation can be derived from Eq. (1) as:

$$\mathrm{CNR} = \frac{\eta P_c \beta c \lambda \tau^2 A_r \mathrm{e}^{-2\alpha Z}}{2hZ^2} \tag{2}$$

where $P_c$ is the peak power. CNR is proportional to $\tau^2$: better range performance with long pulses can be obtained as soon as the range resolution is not an issue.

Fig. 4 plots requested energy/pulse for CNR = 0 dB, for an atmospheric ground wind lidar with following parameters: $\tau = 0.5$ µs, $\mathrm{Ar} = 5 \times 10^{-3}\ \mathrm{m}^2$, $\beta_\pi = 10^{-7}\ \mathrm{m^{-1}\,sr^{-1}}$, $\eta = 0.1$, $\alpha = 0.1\ \mathrm{km}^{-1}$ at 1.55 µm. We observe that, for a 2 km range operational lidar, an energy around 1 mJ is requested, corresponding to a peak power of 2 kW.

Pulse duration impacts on both frequency resolution and range resolution. In terms of range resolution, it should be noted that the length of the scattering volume is $c\tau/2$. In terms of frequency resolution, we can consider that the standard deviation $\sigma_V$ of velocity estimation is inversely proportional to the square of $P_m \tau \tau_g \tau_m$, as a first order of approximation, where $\tau_m$ is the measurement time, $\tau_g$ the duration of the temporal gate and $P_m = P_c \tau PRF$ the mean power of the laser. Consequently, the pulse energy can be traded for the repetition frequency, with an identical pulse duration, without changing either the frequency resolution or the range resolution [11]. Fiber lasers can deliver higher repetition rate than bulk solid state Q-switched lasers, and thus, can counterbalance their relatively low pulse energy as long as mean power is available. The mean power of a 1 mJ, 10 KHz pulsed fiber laser is 10 W. High power pump diodes are then required. Interesting levels (0.29 mJ at 4 KHz ) have been achieved recently, bringing together both energy, spectral and spatial quality [12].

### 4.2. CW Doppler lidar

As another example, let us consider an airborne long range CW lidar for hard target velocity measurement. In this case: $\Re = \rho/\pi$, where $\rho$ is the target albedo ($\rho \leqslant 1$ for a lambertian target). The lidar equation is:

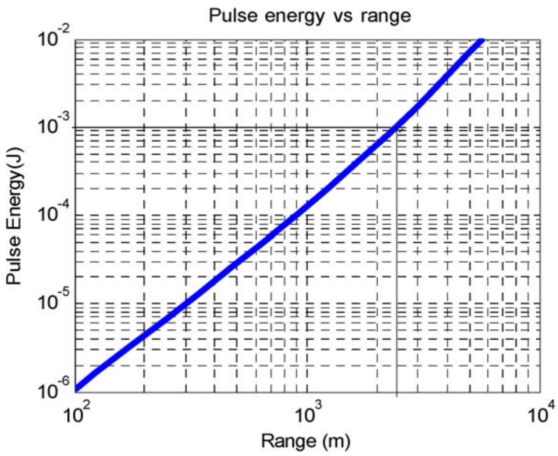


Fig. 4. Plot of Maximum range versus pulse energy for an atmospheric pulsed Doppler lidar.

Fig. 4. Portée fonction de l'énergie émise pour un lidar atmosphérique impulsionnel.

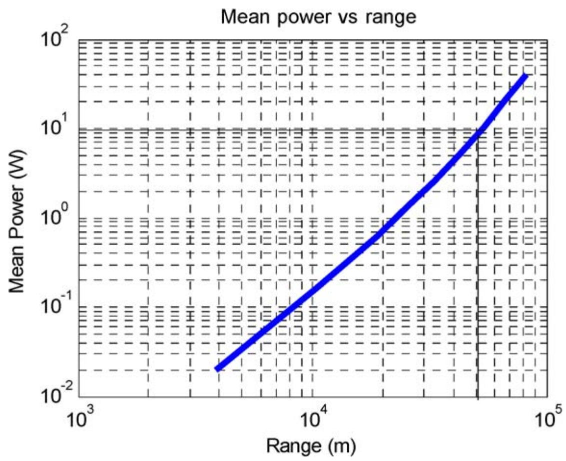


Fig. 5. Plot of Maximum range versus mean power for a hard target CW Doppler lidar.

Fig. 5. Portée fonction de la puissance émise pour un lidar cible dure continu.

$$\mathrm{CNR} = \frac{\eta P_m \rho \lambda A_r \mathrm{e}^{-2\alpha Z}}{\pi h c B Z^2} \tag{3}$$

where $P_m$ is the mean transmitted power. $B$ is most often limited by velocity dispersion and speckle noise. A typical value is $B = 100$ KHz at $\lambda = 1.5$ µm. For a clear atmosphere, Fig. 5 shows the requested power versus range. Lidar parameters are: $\mathrm{Ar} = 5 \times 10^{-3}\ \mathrm{m}^2$, $\eta = 0.1$, $\alpha = 0.01\ \mathrm{km}^{-1}$ at 1.55 µm.

We observe that, as long as the target is larger than the laser spot, the requested mean power is roughly proportional to $Z^2$. Ranges up to 50 km can be reached with 10 W CW lasers.

Such powerful fiber lasers are commercially available but spectral and spatial qualities have to be checked as suitable for use in lidars.

## 5. Spatial quality

In a coherent lidar, detection is only sensitive inside the antenna lobe, corresponding to the diffraction telescope far field. The phase match between the detected signal and the reference local oscillator has to be quite perfect to insure a good mixing efficiency in a narrow field of view.

Low power fiber lasers, using single mode fibers, deliver a perfect Gaussian beam, with a quality factor $M^2 < 1.1$. For local oscillator lasers, spatial quality is not an issue. Most of low power DFB diodes or fiber lasers are pigtailed on SM fibers. However, higher power lasers and amplifiers need larger fiber cores, to store enough energy and to avoid non-linear effects. The single mode operation is not obvious, and large core low aperture number fibers have to be developed. A photonic crystal fiber can be a solution as well [13].

The local oscillator beam is perfectly Gaussian, since it comes from a single mode fiber. If we consider a Gaussian signal beam delivered by the emitter, having a $M^2$ quality factor different from 1 and having the same amplitude radius $\sigma$ on the instrument aperture, the propagated signal and LO beams will not match along the propagation. At long range, the LO divergence $\theta_{\mathrm{lo}}$ is proportional to $\sigma^{-1}$ while the signal divergence $\theta_{\mathrm{s}}$ is proportional to $M^2\sigma^{-1}$. The loss in CNR can be derived from propagation equations and leads to the following equation:

$$\frac{\mathrm{CNR}(M^2)}{\mathrm{CNR}(1)} = \frac{2\theta_{\mathrm{lo}}^2}{\theta_{\mathrm{lo}}^2 + \theta_s^2} = \frac{2}{1 + (M^2)^2} \tag{4}$$

If we accept a loss of 3 dB, the threshold $M^2$ value is $M^2 = \sqrt{3} = 1.73$ (see Fig. 6).

For quasi Gaussian beams, this relation can be used. For fibered lasers having high order modes, such as delivered by photonic crystal fibers, only the central mode participates to the useful signal.

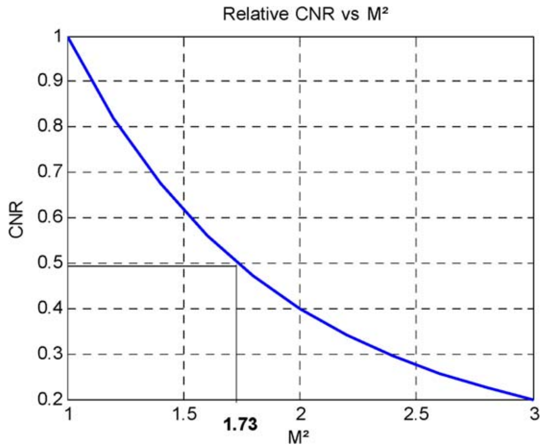


Fig. 6. Relative CNR versus $M^2$.

Fig. 6. CNR relatif en fonction de $M^2$.

## 6. Spectral quality

Coherent detection is based on optical mixing of waves. Apart from spatial phase matching, temporal phase matching is required during the measurement time. Moreover, the return signal is delayed because of propagation time onto the target and back, and spectral shifts during this time have also to be controlled for a Doppler estimation.

### 6.1. Local oscillators

Two kinds of 1.5 μm oscillators are available to design local oscillator sources for coherent lidar applications: the DFB laser diode and the DFB fiber laser. Table 1 shows a comparison between these oscillators in terms of interferometric qualities, essential to carry out coherent detection, but also in terms of system qualities which must be taken into account to implement an operational lidar system.

In term of optical spectrum, a wide band white frequency noise results in a Lorentzian profile and a narrow band white frequency noise result in a Gaussian profile. 'Wide' and 'narrow' should be understood as greater than or lower than the inverse of the measurement time. Since frequency noise may have multiple independent causes, the resulting optical spectrum is the convolution of each profile, leading to a Voigt profile (defined as the convolution of a Lorentzian and a Gaussian profiles).

However, the key parameter for heterodyne detection is the linewidth of the heterodyne current rather than the linewidth of the laser. A laser source which has a Gaussian, Lorentzian or Voigt frequency spectrum will result in a Gaussian, Lorentzian or Voigt heterodyne spectrum since those profiles are stable through convolution.

In the following experiment, the linewidth of the heterodyne current is measured with a fiber interferometer where the optical field in one arm has been decorrelated from the other with a 50 km delay line, corresponding to a resolving power of 20 kHz. Spectrum parameters such as the FWHM (Full Width at Half Maximum), Gaussian FWHM and Lorentzian FWHM are extracted with a maximum likelihood estimator. Fig. 7 shows a good agreement between the measurements (in blue (darker trace)), done on the heterodyne current, and the profile built from the estimated parameters (in red (lighter trace)) in the case of a laser diode.

Table 1
Comparison between lidar oscillator characteristics

Tableau 1
Comparaison des caractéristiques des oscillateurs lidar

| | Wavelength tunability | Spatial quality | Spectral quality | Power | Cost | Compactness reliability |
|---|---|---|---|---|---|---|
| Laser diode | + | + | − | + | + | + |
| Fiber laser | − | + | + | − | − | − |

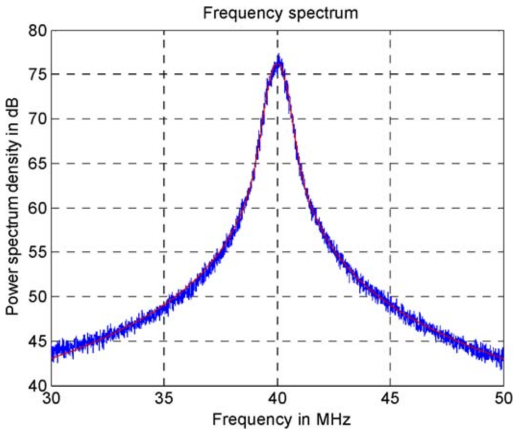


Fig. 7. Frequency spectrum of a laser diode.

Fig. 7. Spectre de fréquence d'une diode laser DFB.

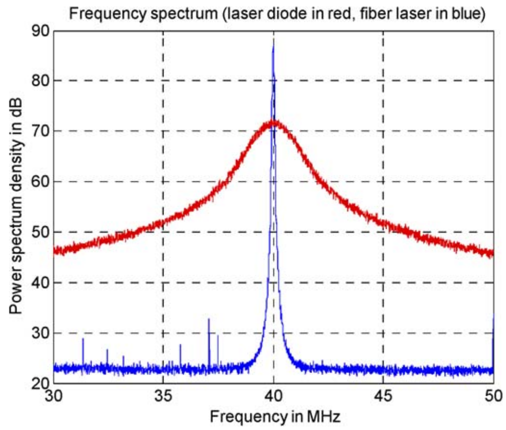


Fig. 8. Laser diode in red (upper trace) and fiber laser spectra in blue (lower trace).

Fig. 8. Spectres d'une diode laser en rouge (haut) et d'un laser à fibre en bleu (bas).

Laser diodes are suitable sources for coherent pulsed lidars as long as their linewidth is smaller or equal to the inverse of pulse duration. In the case of CW lidars, we may need a more coherent laser, such as the fiber laser. The Lorentzian component of the optical spectrum of a fiber laser is so low that it is dominated by other sources of frequency noise. Consequently, we cannot consider that the heterodyne current follows a Voigt profile. Besides its excellent linewidth at half maximum, Fig. 8 illustrates the fact that fiber lasers are characterized by a quasi absence of Lorentzian component: the spectrum of the heterodyne current does not leak around the intermediate frequency.

### *6.2. Continuous wave lidars*

Spectral signal broadening comes from target velocity dispersion, dynamic speckle from target movement, target or lidar vibrations, and atmospheric propagation. It comes also from laser phase noise. For each specific case, the spectral requirement is that phase noise must be negligible compared to other noise source in the useful signal bandwidth.

In CW Doppler lidars, using a monostatic architecture (same Transmitter and Receiver optics) induces an unwanted common mode heterodyne signal due to the interference between the reference beam and transmitted light scattered by the output port. This spurious signal appears at the intermediate frequency $F_i$ whereas the useful signal backscattered by the target is Doppler shifted: Fig. 9 illustrates the spectrum of a CW Doppler lidar, composed of common mode and signal heterodyne currents. The Doppler signal cannot be detected when it is below the spurious spectrum tail. The smaller the Doppler frequency shift, the more demanding are the spectral requirements.

For anemometry for example, wind speeds can be low. To limit the spectral gap around null velocities, oscillator linewidths smaller than 1 MHz at −50 dB are required. This is the reason why available DFB Laser Diode cannot be

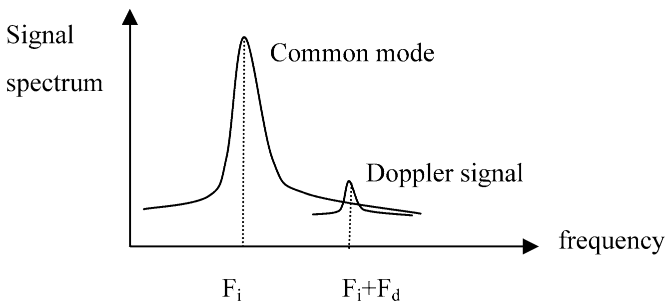


Fig. 9. Doppler signal in presence of common mode.

Fig. 9. Signal Doppler en présence de mode commun.

used as a master oscillator in CW anemometer lidar based on a monostatic architecture, and therefore the fiber laser is the only suitable candidate.

### *6.3. Pulsed lidars*

Two time scales have to be taken into account: pulse duration, and round-trip time. For each characteristic time, a spectral linewidth is required. The laser requirement can be summed up in the Allan curve.

- Pulse duration: the pulse must be Fourier limited. If $\tau_L$ is the pulse duration, the spectral broadening during $\tau_L$ must be much smaller than $1/\tau_L$. We assume that the spatial resolution is matched to the pulse duration.
- Round-trip time: frequency shift during $t = 2Z/c$, where $Z$ is the target range, must be smaller than the expected frequency accuracy, depending on the pulse length, CNR, and number of averaged pulses.

For example, for a 0.5 µs pulse and a 0.5 m/s velocity accuracy, the linewidth must be smaller than 2 MHz in 0.5 µs and smaller than 665 kHz in 12 µs. In this case, both laser diode or fiber laser can be used.

In pulsed lidars, the detection benefits from a temporal selectivity between the common mode due to monostatic architecture, and the signal backscattered by the target. There is thus no frequency gap because of the laser spectral width.

## 7. Random Intensity Noise (RIN)

Intensity noise can affect detection in a coherent lidar. The signal current, the noise current density and the carrier to noise ratio (CNR) can be written as:

$$
\begin{aligned}
\langle i_s^2 \rangle &= 2\eta S^2 P_{\mathrm{lo}} P_s \\
\langle i_n^2 \rangle &= \left[ 2eSP_{\mathrm{lo}} + (S\mathrm{NEP})^2 + \frac{4kT}{R} + (SP_{\mathrm{lo}})^2 \cdot 10^{0.1\mathrm{RIN}} \right] B \\
\mathrm{CNR_{dB}} &= 10 \log_{10}\left( \frac{\langle i_s^2 \rangle}{\langle i_n^2 \rangle} \right)
\end{aligned}
\tag{5}
$$

with $\eta$: lidar efficiency, $S$: detector sensitivity (A/W), $P_{\mathrm{lo}}$: optical local oscillator power (W), $P_s$: optical signal power (W), $B$: electronic bandwidth (Hz), NEP: noise equivalent power density ($\mathrm{W\,Hz^{-1/2}}$), $k$: Boltzmann constant (J/K), $T$: temperature (K), $R$: load resistance (Ω).

The first noise term is the local oscillator photon noise contribution, the second the obscurity current noise contribution, the third is the thermal noise, and the last the contribution of the random intensity noise. When the first term is predominant, the lidar equation leads to Eq. (1). A trade-off must be found between a high local oscillator level on the detector, allowing a photon noise limited detection, and a low value limiting the RIN. For typical values ($\mathrm{NEP} = 10^{-11}\ \mathrm{W\,Hz^{-1/2}}$, $R = 200\ \Omega$, $B = 1$ MHz, $S = 1$ A/W) Fig. 10 shows the CNR versus the Local Oscillator power, for different RIN values.

For RIN better than −160 dB/Hz, only one dB loss is observed. This gives the threshold value for the master oscillator RIN in a single detector configuration. The RIN issue is generally solved by using a balanced detection in the lidar system [14]. Correlated intensity noise is subtracted on both detectors, while opposite phase lidar signals are added.

The required optimal LO power is around 1 mW on the detector and comes from a derivation of the fibered master oscillator.

Laser diodes present a more important RIN than fiber lasers at high frequencies. Their relaxation peak is around 1 GHz whereas that of a fiber laser is nearer 1 MHz. Figure compares typical RIN evolutions versus frequency for a Koheras Fiber Laser and a JDS Laser Diode. Relaxation oscillation peak can be reduced by controlling the pump power using a feedback circuit [15].

At low frequencies, RIN values are lower for laser diodes but do not decrease with frequency. Fiber lasers present relaxation peaks around 1 MHz but are photon noise limited above some tens of MHz. As far as the RIN is concerned, laser diodes can be used on pulsed coherent lidars using balanced detection. Fiber lasers are preferred for CW lidars. Operation in the low velocity domain requires however a balanced detection for relaxation RIN cancellation.

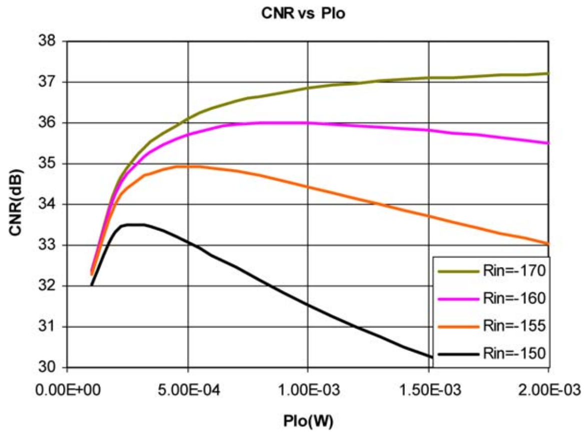


Fig. 10. CNR (dB) versus Local Oscillator power for different RIN values.

Fig. 10. CNR (dB) selon la puissance d'Oscillateur Local pour différentes valeurs de RIN.

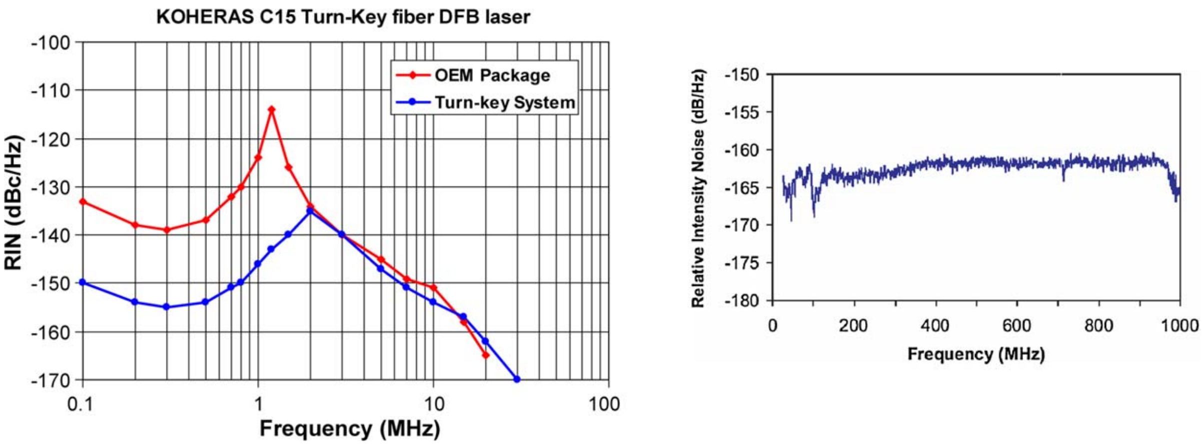


Fig. 11. RIN figures for a DFB diode and a DFB fiber laser.

Fig. 11. Figures de RIN pour une diode laser DFB et un laser à fibre DFB.

## 8. Polarization

To interfere, local oscillator beam and signal beam must have the same polarization state. Signal fading is observed when non-PM fibers are used. Polarization rotations can arise from thermal inhomogeneities, vibrations, or twists and bends in fiber links between components. Lidar designers can use either a polarization controller [16] or PM fibers [17] for stabilizing the polarization state and maximize heterodyne efficiency. The best solution is, however, to develop polarization maintaining fiber amplifiers that maintain a linear polarization state along the laser stages. A technological effort is requested to build large mode area doped fibers having a polarization maintaining structure. Other critical components, such as bundles for pump coupling are needed as well.

## 9. Conclusion

Recently developed fiber lasers open a new area in lidar development, thanks to their spatial and spectral qualities. Large efforts in telecom technology around the world have contributed to promote Er–Yb silica fiber lasers as reliable and cost effective sources for scientific applications. Having a good electric to optic efficiency, they benefit from the atmosphere transparency and eye safety. Pulsed or CW operation is possible with similar designs and waveform flexibility is an asset. Up to now, some operational coherent lidars have already flown with Er–Yb lasers with success [16,17]; the quick rise in laser energy and new spectral bands availability will increase this trend [18–21].

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