Feasibility study of microwave modulation DIAL system for global CO2 monitoring

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Abstract

A new concept of DIAL (DIfferential Absorption Lidar) system for global CO2 monitoring using microwave modulation is introduced. This system uses quasi-CW light which are intensity modulated in microwave region, and receives a backscattered light from the ground. In this system, ON/OFF wavelength laser lights are modulated with microwave frequencies, and received lights of two wavelengths are able to be discriminated by modulation frequencies in electrical signal domain. Higher sensitivity optical detection can be realized compared with the conventional microwave modulation lidar by using direct down conversion of modulation frequency. The system also has the function of ranging by using pseudo-random coding in modulation. Fiber-based optical circuit using wavelength region of 1.6 micron is a candidate for the system configuration. After the explanation of this configuration, feasibility study of this system on the application to global CO2 monitoring is introduced.

Introduction

According to the increasing of atmospheric CO2 concentration caused by the rapid economic growth and industrialization, the need for global CO2 monitoring DIAL system is getting increasing. Recently, conventional coherent and incoherent lidar systems have been studied for application to this DIAL[1-3], but final conclusion about the best system configuration has not been determined yet. Here, we introduce a new concept of DIAL system and the results of feasibility study on application to global CO2 monitoring. This system uses quasi-CW light and measures the CO2 concentration of total column. In this system, ON/OFF wavelength laser lights are modulated with microwave frequencies, and received lights of two wavelengths are able to be discriminated by modulation frequencies in electrical signal domain. In addition to the conventionally reported microwave modulation lidar[4], which enables improvement of SNR (Signal to Noise Ratio) using longtime coherent accumulation of a detected signal, we newly realize narrowband and high response optical detection by using direct down conversion of modulation frequency from microwave region to base-band. Furthermore, we also add the function of ranging, which is needed to know a satellite altitude and to discriminate signals from the ground and the clouds, by using pseudo-random coding in modulation. A 1.6 micron fiber-based optical circuit is a candidate for the configuration of this system, since flexibility and reliability is easily realized in this wavelength region. After the explanation of the system configuration, feasibility study of this system on the application to global CO2 monitoring is introduced.

System configuration

System configuration is shown in Fig. 1. The optical circuit is fiber-based and utilizes COTS components used in optical communication systems. CW laser lights of 1.6 micron wavelength region transmitted from two LDs are intensity modulated with microwave modulation signal. Optical career frequencies of two lights are locked on the ON and OFF wavelength for a CO2 absorption line and locked by a wavelength locking circuit. Career frequencies of two microwave modulation signals have different base-band offset (fm1 and fm2) to each other from a microwave frequency fm. The modulations with different microwave frequencies are for discrimination of ON and OFF components after receiving. The modulated lights are amplified by a fiber amplifier after combined with an optical coupler. The amplified lights of ON/OFF wavelengths are transmitted to a target simultaneously trough a beam expander, and a backscattered light is received by an optical antenna. After rejection of background light with an optical filter, the received light is demodulated by an intensity modulator with a microwave demodulation signal. Career frequency of the demodulation signal (fm in Fig. 1) is slightly different from the modulation frequencies. This intensity modulation acts as microwave frequency mixing and the modulation frequency of received light is directly down-converted from microwave region (fm+fm1 and fm+fm2) to base-band (fm1 and fm2). The demodulated light is converted to an electrical signal using direct detection by a photo detector. Because of the effect of the direct down conversion, a trans-impedance gain of the photo detector can be very high, and a high sensitivity optical detection can be realized. The detected signal is processed by a signal processor using FFT, and amount of differential absorption between two wavelengths is measured from detected intensities of two base-band frequency components where Doppler frequency shifts are negligible.

Code modulation/demodulation is additionally used for ranging and the signal flow on ranging is shown schematically in Fig. 2. A pseudo-random code is generated and the two modulation signals are coded. The same code is delayed by a delay line and the demodulation signal is coded with the delayed code. Only if the delay time fits to the time-of-flight of the light signal to the target, the code is ideally demodulated and an intensity waveform of the demodulated light becomes purely sinusoidal. Thus ranging can be done by searching the delay time which makes intensity of the detected signal maximum in frequency domain. This ranging function also can be used to extract the signal from the target range in the case of multiple target case.

Feasibility study on application to global CO2 monitoring

A priori system requirement, atmospheric conditions, and target conditions used in this feasibility study are summarized in Table 1. The data refresh rate corresponds to the 70km horizontal resolution under the condition of 7km/s foot print speed. The atmospheric and aerosol model are the default 1976 U. S. standard atmosphere (CO2 concentration: 330ppm) and the rural model of VIS=23km. The ON wavelengths are selected around 1.6 micron from candidates shown in ref. 5, and is 1.5804951 micron. The transmittance related to CO2 absorption corresponds to this wavelength and the used atmospheric model. The transmittances shown in the table are those from the satellite to the ground.

Estimated system parameters are listed in Table 2. The laser wavelengths are set at 1.58 micron range for

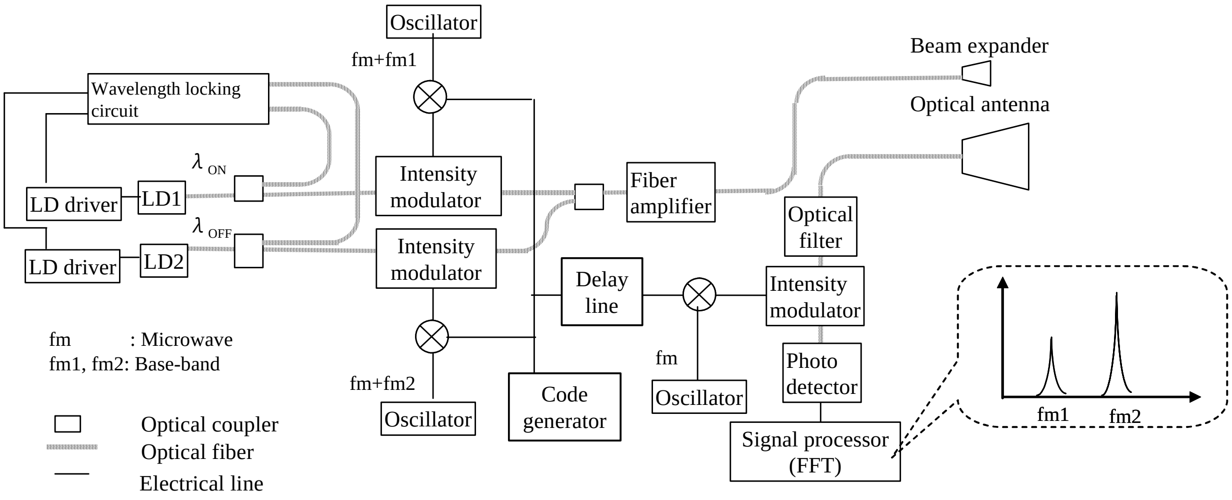


Figure 1. System configuration.

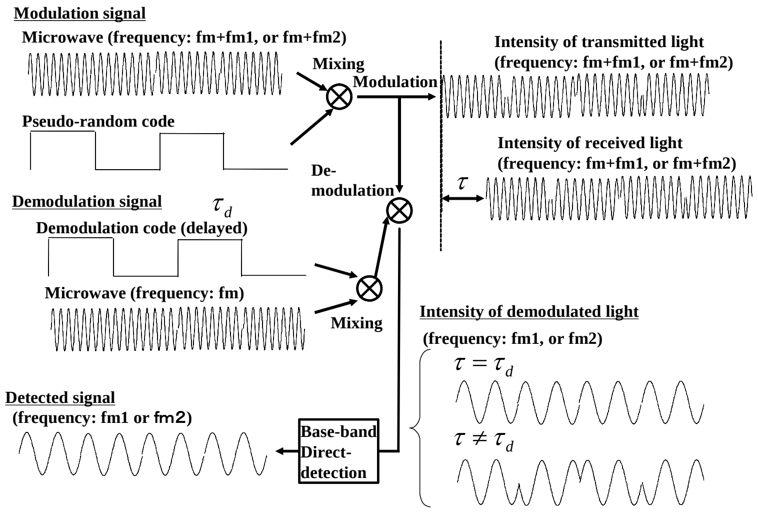


Figure 2. Signal flow chart on ranging.

both ON and OFF wavelength. The difference of two wavelengths is assumed to be negligible in the calculation of SNR using lidar equation. The trans-impedance gain of the detector is set as a variable parameter depending on the receiving bandwidth. InGaAs PIN PD is assumed to be used in the photo-detector since optical detection in this system is performed with very high trans-impedance gain and shot noise of received light including background light is supposed to dominate the detector noise. Dark current is reduced to be negligible by TE cooling to about 270K. The demodulation efficiency is the characteristic parameter of the microwave modulation lidar and the value denoted in Table 2 is the optimized one.

The required SNR can be obtained using Monte-Carlo simulation. In the simulation, signals and noises of On and OFF wavelengths are generated by a computer according to the differential absorption, the SNR, and the corresponding random process. After summation of the signal and the noise, they are processed by actual algorithm. Statistical estimation accuracy of CO2 concentration is calculated from the estimation accuracy of the differential absorption. The denoted required SNR is in the case of accumulation number of 1 and is proportional to $N^{-0.5}$ (N: accumulation number).

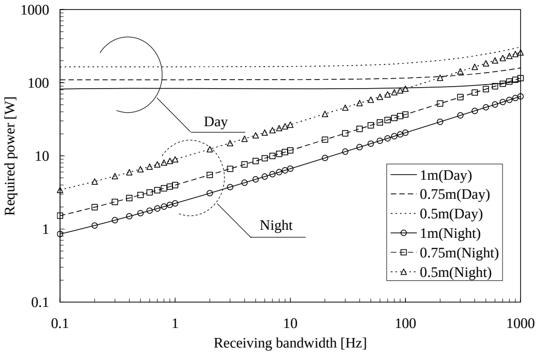
Figure 3 show the calculated required output average power using values listed in Table 1, Table 2, and lidar equation. The lidar equation has the same form as that of the incoherent (direct-detection) lidar. The horizontal axis is the receiving bandwidth related to the trans-impedance gain and the accumulation number. The accumulation number is obtained by dividing the receiving bandwidth by the data refresh rate. In the day time condition, the ground radiance denoted in Table 1 is assumed, and the radiance is neglected in the night time condition. It is shown that larger output powers are required in day time condition especially for narrow bandwidth and high trans-impedance gain. This is because the shot noise of background light dominates the detector noise in this region. By narrowing the FOV, this noise can be decreased, and if the FOV is narrowed to 10 micro radians, the required power becomes almost the same as that for the night condition. However in this case, lag angle caused by foot print moving becomes not negligible and a lag angle compensator is additionally needed. The summary of required power in the case of night time condition is shown in Table 3.

Table 1. A priori conditions for feasibility study.

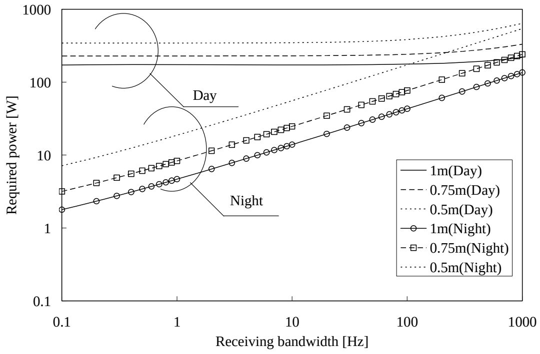
Parameters		Value
System requirement	Satellite altitude	450 km or 650 km
	Data refresh rate	0.1 Hz
	Measurement accuracy	1 % or 1 ppm
Laser transmittance	Transmittance related to CO2 absorption for ON wavelength	0.86
	Transmittance related to other than CO2 absorption	0.92
Target condition	Albedo	0.1
	Ground radiance	9.0 W/m2/sr/μm

Table 2. Estimated system parameters.

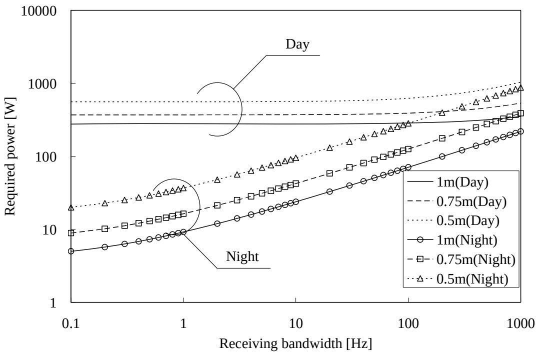
Component	Parameter	Value
Transmitter	Laser wavelength	1.58 micron
Optical antenna	Aperture diameter	50cm, 75cm, 100cm
	Transmittance	-0.5dB
	FOV (Field Of View)	2 mrad
Optical filter	Transmittance	-1 dB
	Band-pass wavelength width	0.1 nm
Photo-detector	Avalanche gain	1
	Excess noise factor on avalanche gain	0
	Dark current	1 pA
	Operating temperature	300 K
	Noise figure	1
	Trans-impedance gain – Bandwidth product	10^{11} ohm Hz
	Quantum efficiency	-1dB
Modulator/Demodulator	Transmittance	-1dB
	Demodulation efficiency	-5.5dB
Other	Required SNR without accumulation for ON wavelength (detected signal domain)	48 dB for 1% accuracy 58.5 dB for 1ppm accuracy



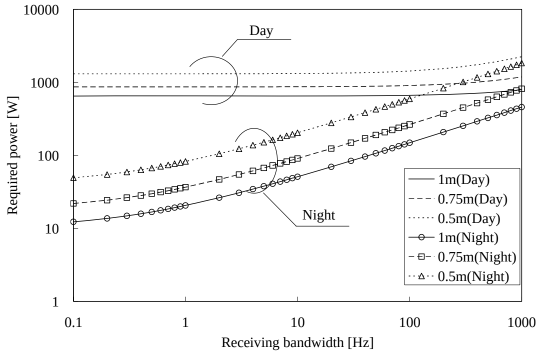
(a)Altitude: 450km, Accuracy: 1%



(b) Altitude: 650km, Accuracy: 1%



(c) Altitude: 450km, Accuracy: 1ppm



(d) Altitude: 650km, Accuracy: 1ppm

Fig. 3. Required output average power versus receiving bandwidth.

Table 3. Summary of required power.
(Night time condition, Aperture diameter: 100cm, Bandwidth: 10Hz, Unit: W)

Altitude Accuracy	450km	650km
1%	7	14
1ppm	24	51

Conclusions

A new concept of DIAL system for global CO2 monitoring using microwave modulation was introduced. ON/OFF wavelengths are discriminated by the modulation frequency, and higher sensitivity optical detection can be realized compared with the conventional microwave modulation lidar by using direct down conversion of modulation frequency. The system also has the function of ranging by using pseudo-random coding in modulation. Fiber-based optical circuit using wavelength region of 1.6 micron is a candidate for the system configuration. Application of this system to global CO2 monitoring was studied based on some a priori conditions, estimated system parameters, and lidar equation. Narrowing of FOV is the important issue to enable day time measurement. In the case of night time, the required output average power for the transmitter is 7W for the accuracy of 1% and the altitude of 450km, and 14W for the altitude of 650km. The required power is 3.5 times higher to obtain 1ppm accuracy in both altitude cases.

References

1. G. J. Koch et al., Appl. Opt., 43, pp. 5092-5099, 2004.
2. M. W. Phillips et al., Proc. of 13th Coherent Laser Radar Conference, pp. 118-121, 2005.
3. P. H. Flamant, Proc. of 13th Coherent Laser Radar Conference, pp. 110-113, 2005.
4. W. L. Eberhard and R. M. Scotland, Appl. Opt., 19, pp. 2967-2976, 1980.
5. R. T. Menzies and D. M. Tratt, Appl. Opt., 42, pp. 6569-6577, 2003.