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Ultra-broadband hybrid infrared laser system

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ABSTRACT

A hybrid IR laser system consisting of molecular gas lasers with frequency conversion of laser radiation in a solid-state converter (nonlinear crystal) was developed. One of these gas lasers is a carbon monoxide laser operating in multi-line or single-line mode. Another one is a carbon dioxide laser operating in multi-line mode. The two lasers operate under Q-switching with a joint rotating mirror. Due to sum- and difference-frequency generation in nonlinear crystals, the laser system emits within wavelength range from 2.5 to 16.6 μm. The laser system emitting radiation over such an extremely wide wavelength range (2.7 octaves) is of interest for remote sensing and other applications connected with laser beam propagation in the atmosphere.

1. Introduction

Remote sensing and other applications (e.g. infrared testing of pipelines, optical wireless communications, optical power transmission and others) connected with propagation of a laser beam in the atmosphere require a laser operating within the IR atmospheric windows. Three atmospheric transparency windows can be identified in the mid-IR range (wavelength from 3 to 50 μm, International standard ISO 20473:2007) with wavelength ranges (roughly): from 3 to 5 μm (1st window); from 8 to 14 μm (2nd window); from 16 to 24 μm (3rd window) (Fig. 1). We develop a simple laboratory laser system that can operate in three atmospheric windows.

The laser system consists of well-known carbon monoxide (CO) and carbon dioxide (CO_2) lasers operating on molecular rotational-vibrational transitions and a solid-state frequency converter made of a nonlinear crystal. Emitting in the spectral range from 9.2 to 10.8 μm, CO_2 laser as a part of the system just operates in the 2nd atmospheric window [1]. Emitting in the very wide wavelength range from 2.5 to 8.3 μm [2], CO laser as a part of the system just operates within the 1st atmospheric window (see fundamental [3] and first-overtone [4] CO laser lines in Fig. 2a and b respectively) and partially in the 2nd atmospheric window (in high vibrational bands with wavelengths longer than 8 μm). To enrich CO laser spectrum, a frequency conversion in a nonlinear $ZnGeP_2$ (ZGP) crystal was applied in Ref. [3,5,6]. The number of spectral lines increased from 150 CO laser lines to at least 670 emission lines in the wavelength range from 2.5 to 8.3 μm [6] due to sum-frequency generation (SFG) and difference-frequency generation (DFG). Hundreds of new spectral lines were obtained within the 1st atmospheric window (spectral lines obtained due to SFG process as the first stage and DFG process as the second stage of the two-stage frequency conversion are shown in Fig. 2, spectra c and d respectively). Dozens of DFG spectral lines (Fig. 2, spectrum d) almost overlap spectral gap between fundamental and first-overtone vibrational bands of the CO laser (Fig. 2, spectra a and b) except a narrow spectral gap between 4.2 and 4.3 μm (Fig. 2, spectral interval g) because of strong absorption in atmospheric CO_2.

The crystal ZGP has high second-order nonlinear coefficient but it is transparent only up to 12 μm in the mid-IR range. To expand and enrich the spectrum of the laser system, we used other nonlinear crystals for frequency conversion of the CO and CO_2 laser radiation due to SFG and DFG. For the frequency conversion we chose crystals $AgGaSe_2$ (AGSe) and GaSe because they transparent up to 18 μm and have high enough second-order nonlinear coefficient. Previously, AGSe crystal was chosen in Ref. [8] and GaSe crystal was chosen in Ref. [9] for frequency conversion of CO laser emission. A nonlinear $CdGeAs_2$ (CGA) crystal was chosen in Ref. [10] for frequency conversion of CO and CO_2 laser radiation, however CGA crystal is not commercially available due to difficulties of growing the high optical quality crystal [11, p. 387].

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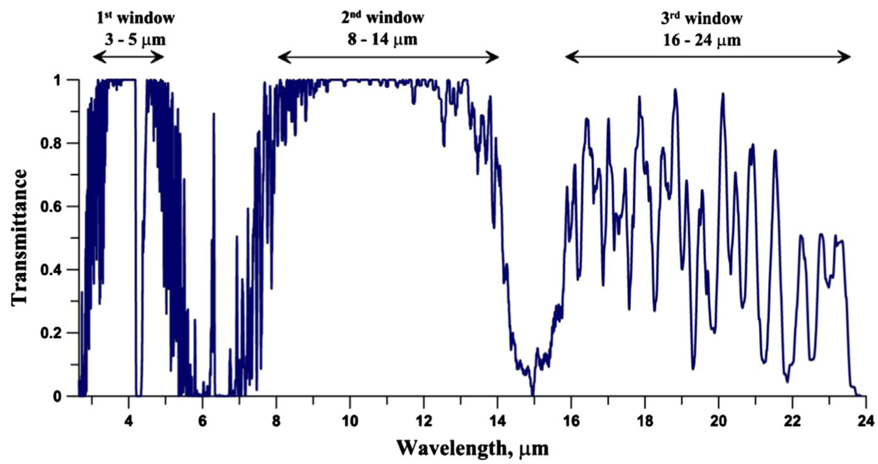

Fig. 1. (Color online) Transmittance spectrum of the atmosphere calculated from the HITRAN database [7] (USA model, mean latitude, summer, temperature 296 K, pressure 1 atm, optical path 100 m) and three atmospheric windows.

2. Experimental setup

2.1. Gas lasers

In our experiments, we studied the following combinations of gas lasers: (1) low-pressure cw multi-line CO and CO_2 lasers; (2) high-pressure pulsed single-line CO laser and low-pressure cw multi-line CO_2 laser.

The first gas laser system consisted of homemade low-pressure CO and CO_2 lasers pumped by a dc glow discharge [12]. Both lasers operated in a repetitively pulsed mode with synchronous Q-switching by a joint rotating mirror RM (Fig. 3) and produced laser pulses with a repetition rate of 100 Hz and pulse duration of 1.2 μs (FWHM) in the case of CO laser and 0.3 μs (FWHM) in the case of CO_2 laser.

2.1.1. Low-pressure CO laser

Flat metallic mirrors M1 and M2 (Fig. 3) were used as rear mirrors in the two laser resonators. Broadband interference mirrors were used as output couplers C1 (transmittance $T=8\%$ at 5.0 μm) and C2 ($T=27\%$ at 9.5 μm). To form stable laser resonators,

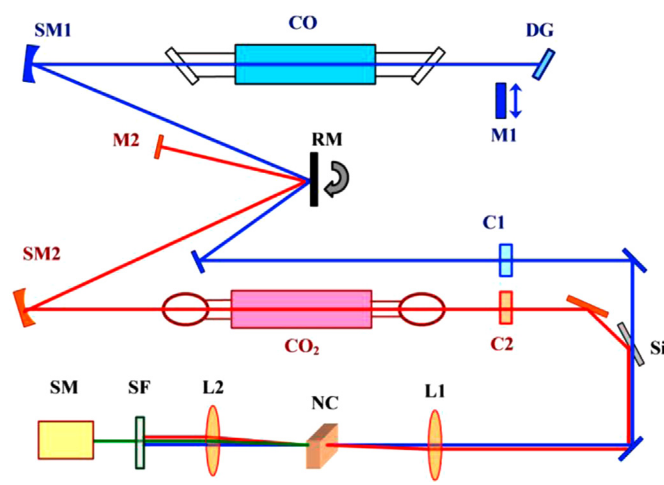

Fig. 3. (Color online) Hybrid laser system consisting of Q-switched CO and CO_2 lasers and nonlinear crystal NC that includes diffraction grating DG, rear mirrors M1 and M2, spherical mirrors SM1 and SM2, rotating mirror RM, output couplers C1 and C2, silicon wafer Si, lenses L1 and L2, spectral filter SF, and spectrometer SM.

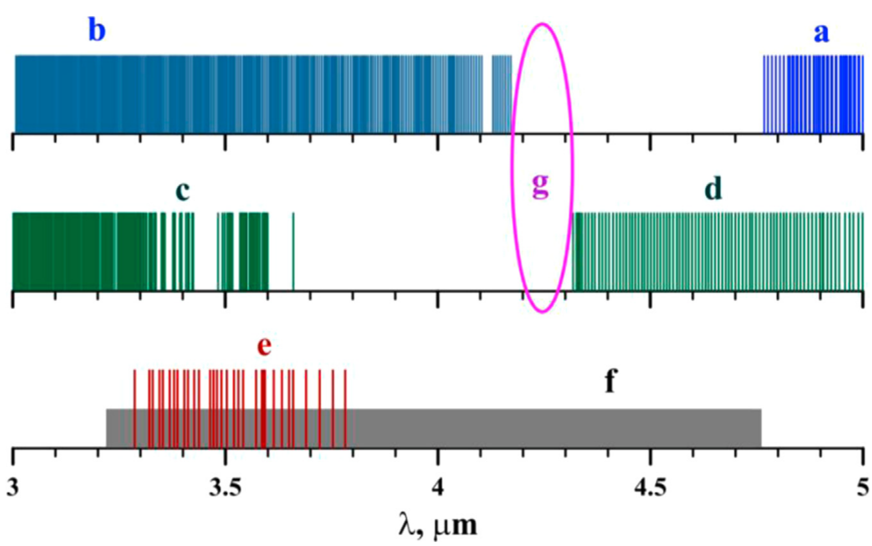

Fig. 2. (Color online) Spectrum of the hybrid laser system within the 1st IR atmospheric window (from 3 to 5 μm) that includes (a) fundamental CO laser lines [3], (b) first-overtone CO laser lines [4], (c) SFG lines under mixing CO laser lines [6], (d) two-stage frequency conversion under mixing CO laser lines [6], (e) SFG lines under mixing CO and CO_2 laser lines obtained in this paper, (f) thousands of SFG lines calculated for mixing CO and CO_2 laser lines, and (g) spectral gap because of absorption in atmospheric CO_2.