Research on a middle infrared and long infrared dual-band laser

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Received May 20, 2011; accepted September 27, 2011; posted online November 25, 2011

We propose a continuous-wave (CW) middle infrared (MIR) and long infrared (LIR) dual-band laser for the calibration and effect research of infrared detecting and imaging systems. A total output power of 18 W is achieved by the proposed dual-band laser through one DF gain medium module and one parallel placed CO_2 gain medium module using a common stable resonator and output mirror with nominal transmissivities of ∼5% in the MIR band and ∼10% in the LIR band. Spectra of dual-band laser are acquired. The power extracting efficiency of this dual-band laser can be significantly improved, as validated by a single-band test of optimized parameters.

OCIS codes: 140.3070, 110.3080, 140.1550, 140.3470.

doi: 10.3788/COL201210.031404.

Infrared (IR) detecting and imaging systems are being developed rapidly for their important applications in such domains as surveillance and reconnaissance, target acquisition, engagement, and missile guidance[1−3]. Middle IR (MIR, 3–5 μm) and long IR (LIR, 8–12 μm) are in the atmospheric window. Currently, the most advanced IR imaging system of the third generation is a dual-band imaging system with both MIR and LIR ranges. Dual-band images provide rich information on the target, which can improve detection precision[2,4,5]. Studies on topics, such as MIR and LIR dual-band detectors[6,7], optical system[2,8], film coating[9], and laser sources[10,11], have already been developed or currently ongoing.

Our research on a continuous wave (CW) MIR and LIR dual-band laser is reported in this letter. Evidently, the proposed laser can be used for more functional calibration and effect research on MIR and LIR dual-band detecting and imaging systems. Furthermore, it has important application prospects in directed IR countermeasure or forward-look IR systems.

The schematics of the MIR and LIR dual-band laser are shown in Fig. 1, and a photograph of the proposed dual-band laser is shown in Fig. 2. The gain medium of the proposed dual-band laser was formed by two kinds of gain modules (MIR gain module and LIR gain module) placed parallel to each other. The gain medium of the MIR band was generated in the DF gain generator as DF chemical laser through the following cold pumping reaction:

$$F + D_2 \rightarrow DF(v \leqslant 4) + D. \qquad (1)$$

The F atom is dissociated from NF_3 mixed with helium in the high-voltage direct current glow discharge tube 1, which was used in our previous research[12]. The dissociation reaction is

$$NF_3 + He \xrightarrow{e} NF_{3-i} + iF + He. \qquad (2)$$

The gain medium of the LIR band is generated in the CO_2 gain generator as CO_2 laser through the following energy transfer pumping reaction:

$$N_2(v = 1) + CO_2(00^00) \rightarrow N_2(v = 0) + CO_2(00^01). \qquad (3)$$

The excited molecular $N_2(v{=}1)$ is generated from ground state $N_2(v{=}0)$ mixed with helium in the high-voltage direct current glow discharge tube 2, in which the excitation process was

$$N_2(v = 0) + He \xrightarrow{e} N_2(v = 1) + He. \qquad (4)$$

Dual-band laser power was extracted by common stable resonator composed of the reflection mirror and the output mirror. The effluent gas was cooled by the heat exchange, and exhausted by the vacuum pump system.

Furthermore, the control systems of the DF and CO_2 gain modules, the two ∼200-mA, 3–4-kV discharge power supplies and the gas supply systems in this laser were separate; thus, each gain module could be operated independently to output single-band laser.

Some key technologies to be considered seriously in the design of the proposed dual-band laser are the gain zone length and peak position, cavity pressure, and transmissivity of the output mirror. Otherwise, the power extracting efficiency may be too low to support running the proposed dual-band laser.

One key technology is matching the peak gain positions of the DF medium and CO_2 medium. Theoretical analysis found that the peak gain position of the DF

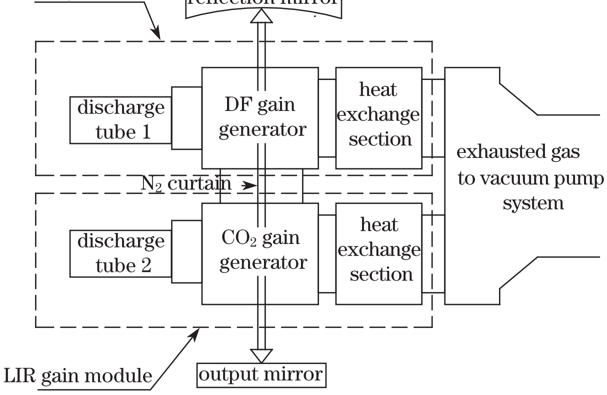

Fig. 1. Schematics of the MIR and LIR dual-band laser.

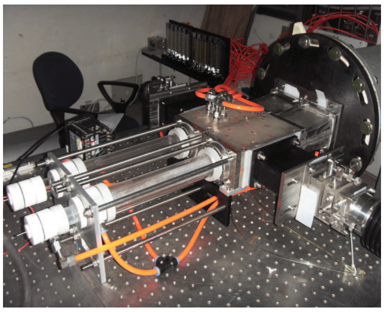

Fig. 2. Photograph of the MIR and LIR dual-band laser.

medium was further ahead than the CO_2 medium, and the gain zone length of the DF medium was much shorter than that of the CO_2 medium. Hence, the D_2 and CO_2 gas injection orifices and gas flow channel with detailed geometrical dimensions in the proposed dual-band laser were designed as shown in Fig. 3. The design included five rows of CO_2 gas tubes; however, only one row of D_2 gas tubes. The D_2 and CO_2 gas injection orifices was interlaced on those tubes. This single row of D_2 gas tubes was placed 2 mm before the fifth row of CO_2 gas tubes. Compared with the immovable D_2 gas injection orifices, CO_2 gas could be injected into the gas flow channel selectively through any one, two, or several rows of the tubes by outer gas valves with a rotameter. Thus, the start position and length of gain zone for the CO_2 medium could be changed, and the peak gain position matching of the DF medium and CO_2 medium could be achieved to a certain extent. Moreover, according to the calculating result of flow mass flux conservation, the diameter of CO_2 gas injection orifices was larger because the molecular weight of CO_2 is greater than that of D_2.

Another key technology is matching the cavity pressure of gas flow in the two gain modules of the proposed dual-band laser. Two methods were adopted synthetically. One method was running the dual-band laser with a low cavity pressure as the typical value 0.2–0.5 kPa of our DF single-band laser, not as the typical value ~1.5 kPa of our CO_2 single-band laser. The other optional method was setting a nitrogen gas curtain between the DF and CO_2 gain modules to form a gradient of pressure distribution and adapt two different cavity pressure values.

Low transmissivity of output mirror was selected conservatively to ensure lasing in both MIR and LIR bands. The nominal transmissivities of output mirror for dual-band laser were ~5% in the MIR band and ~10% in the LIR band, according to the estimated gain coefficients of the two modules. Real transmissivity in the wavelength is shown in Fig. 4, which is the test result from the mirror film-coated supplier. The difference between theory and test is attributed to the thickness of the dielectric film being too thick (up to 20 μm) to control transmissivity precisely.

An output power of 18 W was first achieved by the proposed dual-band laser through the above described two parallel gain modules using a common stable resonator under the following working conditions. The position of optical axis was 3-mm downstream of the D_2 injection orifices, that is, 33-mm downstream of the first line of CO_2 injection orifices. The cavity length of the resonator was 650 mm. The output mirror was a ZnSe piece coated with dielectric film. Real transmissivities in the MIR band (DF: 3.5–4.1 μm) and in the LIR band (CO_2: 9–11 μm) were 3.5% – 5% and 6% – 10%, respectively, as shown in Fig. 4. The radius curvature of the output mirror was ∞, and its dimension was Φ 40 × 5 mm. A diaphragm with a hole diameter of Φ 20 mm was placed in the resonator, near the output mirror end, to prohibit damage of the output mirror, this phenomenon had been observed occasionally in our previous experiments. The reflection mirror with nominal reflectivity ($R \geqslant 99\%$) was composed of a silicon piece coated with golden film. The dimensions of the reflection mirror was Φ 30 × 3 mm with one sphere surface, in which the radius curvature was ~1 000 mm. The output window was an uncoated ZnSe piece with the dimensions of Φ 30 × 3 mm. The cavity pressure was approximately 0.2 kPa.

The emitting spectra of the proposed dual-band laser were measured by a remote sensing Fourier transform IR spectrometer named as Tensor 37 (Bruker IFS®, spectral range of 500–6 500 cm^{-1}; resolution of 0.6 cm^{-1}; single measurement time of ~1 s; wavelength accuracy of 0.1 cm^{-1}). Five frames of the proposed dual-band laser spectrum were measured. The analysis results of the measured dual-band spectra indicate that the compositions of the MIR (DF) and LIR (CO_2) single-band spectr showed nearly no changes. In contrast, the intensities of the DF lines fluctuated markedly, which may have been caused by the acute competition of oscillating lines and unstable working conditions. The intensities of CO_2 lines

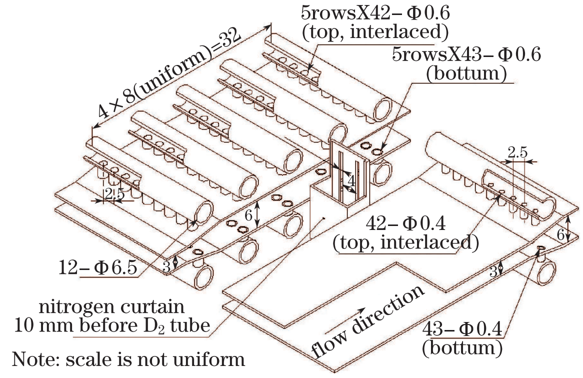

Fig. 3. D_2/CO_2 injection orifices and gas flow channel in the proposed dual-band laser.

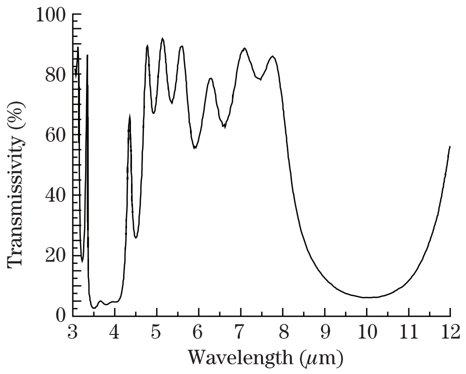

Fig. 4. Real transmissivity in the wavelength of the proposed dual-band laser.

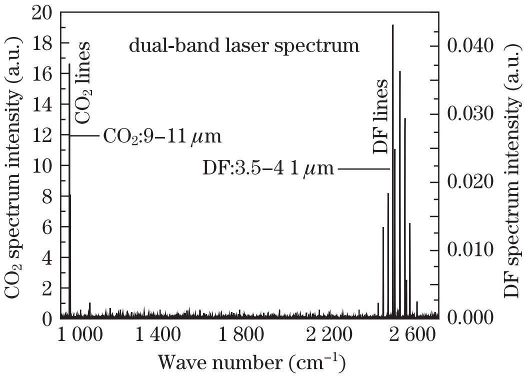

Fig. 5. Typical spectra of the MIR (DF) and LIR (CO_2) dual-band laser.

fluctuated relatively less. A typical spectrum of the proposed dual-band laser is shown in Fig. 5. The compositions of the DF and CO_2 single-band spectra were identified with the reference spectrum data in Refs. [13,14].

Ten lines in the MIR band and three lines in the LIR band were 1P9, 1P11, 2P7, 2P8, 2P9, 2P10, 3P7, 3P8, 3P9, and 3P10 of the DF diatomic molecule, and 10P20, 10P16, and 9P20 of the CO_2 triatomic molecule. The number of CO_2 lines was less than that of DF, and the intensities of CO_2 lines were much higher than those of the DF lines. Two main reasons for this, aside from the above mentioned line numbers, are that the CO_2 output power was bigger than that of the DF and that the response output signal of the MIR sensor was much smaller than that of the LIR sensor in Tensor37. Notably, the third level of DF lines did not overlap the CO_2 lines in the measured data, a phenomenon that always emerges when employing the grating spectrophotometer.

After the success of the 18-W output with a common stable resonator and the validation of the dual-band spectrum, a single-band of MIR was operated by shutting off the CO_2 gas supply, degrading the power from 18 to 7 W, and restored back to 18 W when the CO_2 gas supply was switched on. The single band of LIR was operated by shutting off the D_2 gas supply, thereby degrading the power to 13.4 W. The dual-band output power was slightly smaller than the addition of two single-band output powers, which may have been caused by medium absorptions or a slightly lower cavity pressure in the proposed dual-band laser. In-depth research will be completed in the next investigation stage.

The power extracting efficiency of the proposed dual-band laser can still be improved. First, the transmissivity of the output mirror had been selected conservatively. Furthermore, the transmissivity of the output window, the radius curvature of mirrors, and the cavity pressure have not been optimized in the present stage. Employing several existing mirrors in our laboratory, two single-band modules were operated individually to observe a potential improved output performance.

An output power of 14 W was obtained for the MIR single-band using only the MIR gain module. The parameters of the reflection mirror, output window, and cavity pressure were not changed. However, another output mirror coated with only the DF band film with transmissivity of 10% and radius of curvature of 1 000 mm was used to replace the dual-band output mirror.

An output power of 30 W was obtained for the LIR single-band using only the LIR gain module. The parameters of the reflection mirror and output window mirror were not changed. However, another output mirror coated with the single CO_2 band film with transmissivity of 15% and radius of curvature of 5 000 mm was used to replace the dual-band output mirror, and the cavity pressure was raised from 0.2 to 1.1 kPa.

In conclusion, we demonstrate a MIR (DF: $3-5$ μm) and LIR (CO_2: $8-12$ μm) dual-band laser validated by the measured spectrum. A power of up to 18 W is obtained for the first light of the proposed dual-band laser, with approximately 7-W power in the MIR band measured by shutting off CO_2 gas and approximately 13-W power in the LIR band measured by shutting off D_2 gas. The optical axes of the MIR laser beam and the LIR laser beam are complete with superposition due to the common resonator. Based on 14 W of the MIR and 30 W of the LIR single-band power data with optimized transmissivity of output mirror for each single band, the power extracting efficiency of the proposed dual-band laser can be improved in near future.

The work was supported by the National Natural Science Foundation of China under Grant Nos. 10974255 and 10304025.

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