High-Speed Photonic Device Technologies in Optical Fiber Connected Millimeter-wave Radar System for Foreign Object Debris Detection on Runways

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Abstract

Precise imaging of obstacles and foreign-object debris (FOD) is one of the most important security technologies for avoiding trouble in advance. Recently, we have focused on an optical fiber connected millimeter-wave radar system using a radio over fiver (RoF) technique for effectively detecting FOD over the large area of an airport runway. In this paper, we introduce high-speed photonic devices such as a W-band frequency modulated continuous-wave (FM-CW) signal generator, a highly-sensitive quantum dot (QD) photodetector, and a QD optical frequency comb laser (QD-CML) with harmonically optical pulsation. It is expected that these advanced photonic device technologies will become potential candidates for use in the RoF technique to realize the optical fiber connected millimeter-wave radar system.

1. Introduction

Quick and precise imaging of obstacles and foreign-object debris (FOD) is one of the most important security technologies for avoiding trouble in advance. For example, on an airport runway, a very small amount of FOD probably causes a significant number of accidents. An imaging technique with quick detection and accurate sensing features is necessary to prevent these accidents. The FOD detection system must be capable of detecting a metal cylinder as small as a few cm in size at a distance of approximately 60 m, which is a typical runway width. Millimeter-wave radar is one of the possible candidates for detection of small FOD, and it has the following advantages: anti-fog, anti-dust, and availability in dark situations. However, the millimeter-wave signals are highly attenuated in free space propagation. Consequently, millimeter-wave radar characteristics limit detection coverage (radar range). A sensor network system comprising one master generator and plural antennas (radar heads) connected by optical fibers has been proposed to overcome this problem [1]. This expands the surveillance area; each radar head covers several hundred meters. When one of the radar heads detects FOD, a central station receives the FOD information and informs air traffic controllers at the control tower.

Radio-over-fiber (RoF) technology satisfies the requirements of the aforementioned system [2]. In a distributed radar system, a precision optical signal can be delivered from the central office to each remote radar head through the optical fiber network, as detailed in Fig. 1. The RoF transmits a radio frequency (RF) signal through optical fibers using an E/O (electrical to optical) converter, single-mode optical fibers, and an O/E (optical to electrical) converter. Transmission loss of optical fiber is well known to be greatly smaller than that of RF coaxial cable. Quasi-lossless RoF connection realizes this new design, although conventional RF connection does not allow transmission over several kilometers, as is needed on airport runways. Furthermore, this concept is cost-effective because the expensive signal generator and received signal analyzer are incorporated in the device. In this paper, we introduce potential candidate high-speed photonic devices for the RoF technique in the optical fiber connected millimeter-wave radar system.

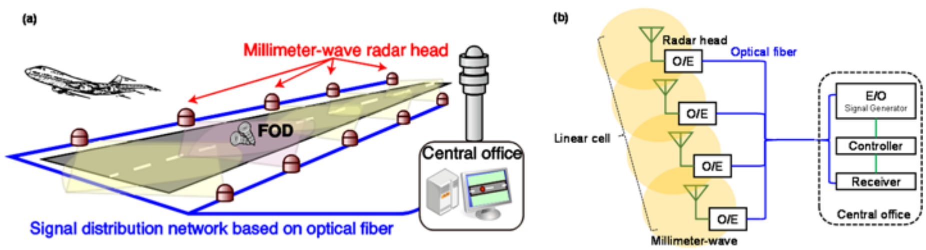

Figure 1: (a) Schematic and (b) block diagram of the distributed radar system connected to an optical-fiber-based signal distribution network.

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2. W-band frequency-modulated continuous-wave (FM-CW) signal generation

High-precision imaging technology for detection of small FOD is desired for surveillance in airport runways and railways; thus, the carrier frequency should be increased to a higher frequency, such as one in the W-band (75–110 GHz). An optical fiber link is one of the possible candidates for the distribution network owing to its broadband and low-loss features. RoF technology is a promising candidate for an optical analog link to distribute millimeter-wave signals. Optical frequency doubling and quadrupling technologies based on an optical modulation technique with direct photonic up-conversion can easily generate and distribute millimeter-wave signals through optical fiber [3]. Here, we demonstrate W-band frequency-modulated continuous-wave (FM-CW) signal generation using this optical modulation technique as shown in Fig. 2(a) [4]. For high-resolution imaging, the ramped frequency bandwidth of the FM-CW signal is set at 8 GHz with a frequency from 92 to 100 GHz; this band is assigned for radiolocation in Japan. An optical frequency quadrupler converts the input signal with a frequency of 23–25 GHz to a millimeter-wave FM-CW signal with a frequency

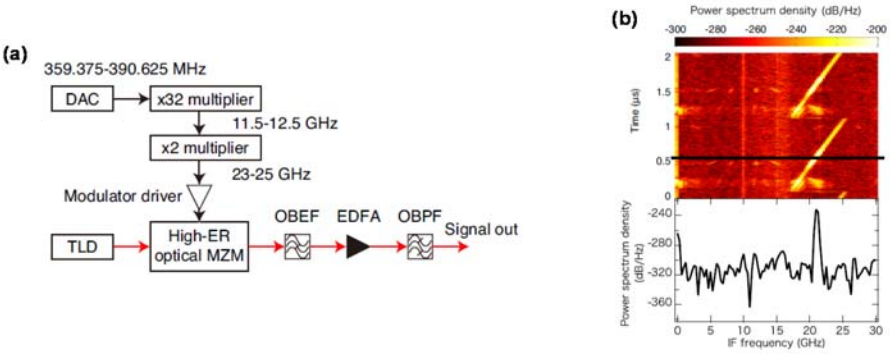

Figure 2: (a) Broadband FM-CW optical signal generator. (b) Spectrogram of the power spectrum density (Top). Corresponding spectrum at the temporal position of the thick black line shown in the top panel (Bottom).

of 92–100 GHz. At the W-band, a uni-traveling-carrier photodiode (which was utilized as the photomixer) directly connected to a W-band full-band amplifier converted the optical FM-CW signal to a corresponding W-band signal. An electrical spectrum analyzer (ESA) with a harmonic mixer was used for measurement of the phase noise and its power spectrum. To observe the temporally evolved behavior, a W-band full-band double balanced mixer (DBM) connected to an electrical local oscillator (LO) operating at 75 GHz performed a frequency down-conversion from the W-band to DC ~ 35 GHz. The down-converted intermediate frequency (IF) component was captured by an analog-to-digital converter (ADC) with 8-bit resolution. For a proof-of-concept demonstration, we used a real-time oscilloscope with a bandwidth of 30 GHz and a sampling rate of 80 GSamples/s as the ADC. We used off-line signal processing to generate a periodogram and a spectrogram of the captured IF signals.

The signal captured by the ADC was processed to form a spectrogram for evaluation of the W-band FM-CW signal as Fig. 2(b). The generated spectrogram showed ramping behavior at the IF from 17 to 25 GHz within 1 μs; the observed sweep rate of the signal was 8×10^{15} Hz/s. No significant ghost or harmonic components were observed in the sliced power spectrum density at any temporal points. The results indicate that a clear frequency-quadrupled FM-CW signal with bandwidth of 8 GHz at the W-band can be generated without any harmonics or undesired components [4]. To evaluate the potential for application in a radar system, detailed discussions are presented as follows. The pulse duration of 1 μs limits the sensing range of the FM-CW-based radar system to a distance of 150 m. However, because the pulse duration can be optimized by the ADC, the sensing range will vary. Additionally, theoretical resolution is one of the most important specifications for the radar system and is obtained by the equation $\Delta d = c/2B$, where Δd, c, and B are the mean resolution, the speed of light, and the bandwidth of the FM-CW signal, respectively. In the case of the 8-GHz-bandwidth FM-CW radar, the resolution is estimated to be approximately 18.8 mm. This radar can be applied for FOD detection on airport runways because the Federal Aviation Administration recommends a standard FOD detector to be a pillar with a diameter of 38 mm and a height of 30 mm for fixed radar systems.

3. Quantum-Dot Photonic Devices for Broadband

3.1 Quantum-Dot Photo-detector for High-speed and sensitive O/E Conversion

Quantum dots (QDs) are semiconductor nanostructures with vast applications in many industries. In QD emission devices such as QD lasers and QD semiconductor optical amplifiers (QD-SOAs), broadband wavelength range operation, low power consumption, and temperature stability can be achieved because quantum confinement in QDs exists in all three dimensions. Recently, we developed a 1.5-μm-wavelength InAs-based QD absorption layer for high-speed photo-detector applications in optical fiber communications [5, 6]. Figure 3(a) shows a schematic cross-sectional image of the developed surface illuminated by a QD photo-detector. A total of 20 stacked QD absorption layers, which comprised four monolayers of InAs QDs and 20-nm-thick InGaAlAs spacer layers, were grown on an InP (311)B substrate using the strain-compensation technique by molecular beam epitaxy [7]. Figure 3(b) shows I-V curves for the dark current and the photocurrent. We obtained a low dark current of less than 1 nA at a reverse bias voltage that ranged from -10 to -20 V. The breakdown voltage of the I-V curve was as low as -28 V. The PIN-based QD structure allowed a photocurrent from low to high bias voltage. It functioned as a simple PIN photodiode at low bias voltage and as an avalanche photodiode at higher bias voltage. At over 20 V, we observed the avalanche multiplication effect, and a factor M of 12 with a dark current of 3 μA was achieved at -27.7 V. For the PIN photodiode at low bias voltage, the 3-dB bandwidth (f_{3dB}) was calculated from the capacitor-resistor (CR) time-constant and the carrier drift time in the depletion layer (QD layer), where a measured capacitance of 36 fF and a resistance of 15 Ohms in the network analyzer were used. We also used the saturated carrier-drift's average velocity of electrons and holes in the QD layer and the traveling distance, which were 6×10^6 cm/s and 0.4 μm, respectively. The maximum calculated f_{3dB} was approximately 50 GHz. However, we also obtained an f_{3dB} value of 20 GHz (M = 1) at a low bias voltage, which was caused by a large parasitic capacitance between the n^+-InP substrate and the electrodes, except at the p-n junction. By employing a semi-insulator substrate instead of the n^+ substrate, we reduced the parasitic capacitance and hence improved the measured 3-dB bandwidth. In the avalanche multiplication region at higher bias voltage, an additional multiplication time parameter should be taken into account for the PIN f_{3dB} calculation. Because the prepared QD absorption layer had multi-quantum well (MQW) structure, a small electron-to-hole ionization coefficient ratio (k factor) can be expected. From the AlGaAs/GaAs MQW avalanche photodiode, a small k factor of 0.12 was obtained owing to the large CB offset in the MQW boundary. By assuming k = 0.2 and M = 10, we estimated a 3-dB gain and bandwidth product (GB product) of 59 GHz, as shown in Fig. 3(c). Here, the 3-dB bandwidth was dominated by the multiplication time. When the total thickness of the stacked InAs QD layer was reduced from 0.4 to 0.1 μm, a high GB product of 150 GHz was obtained. The measured GB product of 45 GHz (indicated by the dot in Fig. 3(c)) agreed well with the GB product from the above calculation.

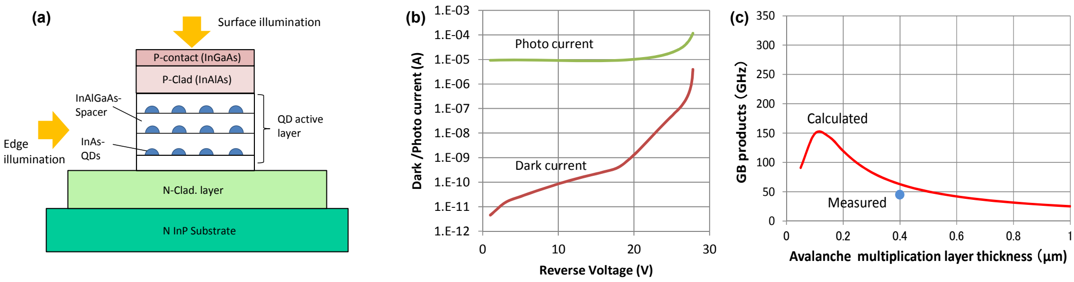

Figure 3: (a) PIN structure with InAs/InGaAlAs QD absorption layer for photodetector. (b) I-V curves for the dark current and photocurrent with avalanche multiplication. (c) GB product curve.

3.2 Optical Frequency Comb Laser and Optical Pulse Generator with Broadband Quantum-Dot Optical Gain

High-repetition optical pulse generation is the most promising technique for realizing a return-to-zero signal for high-speed optical communications, RF clock distribution in photonic networks. As a new technique for optical pulse generation, we have focusing on optical frequency comb generation using QD optical gain [8, 9]. We also focused on the use of an ultrabroadband optical frequency source in a novel wavelength range of the Thousand- and Original-bands (T-band: 1000–1260 nm, 61.9 THz; O-band: 1260–1360 nm, 17.5 THz). In the T + O band, a >70-THz optical bandwidth can be used for a high-capacity access network and/or a large port-counts optical interconnection in a data center or other networking system [9]. We therefore demonstrated high-repetition optical short pulse generation with wide wavelength tunability in the T + O band using the QD-CML [8, 9].

Figure 4(a) shows harmonically mode-locked QD-CML for high-repetition optical short pulse generation. An inset picture is a typical atomic force microscope (AFM) image of the 2.76-monolayer (ML) InAs/InGaAs QD structure. Using the sandwiched sub-nano separator (SSNS) growth technique, a high density QD can be obtained without giant dot formation [9]. The length of the external cavity was fixed at approximately 15 cm for a 1.0-GHz free spectrum range (FSR). A 10th-harmonic mode-locking operation of the external-cavity QD-CML can be simply demonstrated when the applied electrical frequency is fixed at 10 GHz. Figure 4(b) shows an optical spectrum of the external-cavity QD-CML under the 10th-harmonic mode-locking conditions. Fine-teeth optical frequency comb peaks with 10-GHz spacing are clearly observed. Figure 4(c) shows the electrical RF spectrum of the 10-GHz optical pulsation from the 10th-harmonic mode-locked QD-CML. A 10-GHz harmonic peak and a higher-order frequency of 20 GHz are observed in the RF spectrum. A high S/N of approximately -58 dB was observed. This simple optical pulsation technique using broadband QD optical gain is expected to become a useful and attractive method for RF clock distribution in network systems.

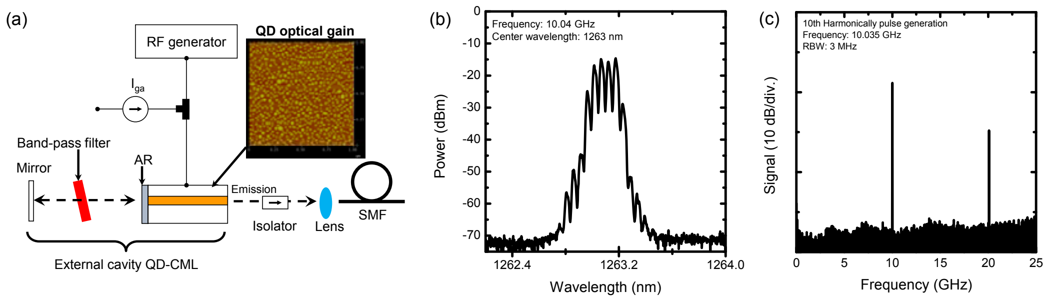

Figure 4: (a) Optical Setup, and (b) Optical and (c) RF spectra of the 10th-harmonically mode-locked QD-CML.

5. Conclusion

We reported an optical fiber connected millimeter-wave radar system for quick and effective detection of foreign-object debris (FOD) in the large area of an airport runway. It is expected that the advanced photonic device technologies used for the radio-over-fiber (RoF) technique will become useful for further realizing the advantageous radar system proposed. In this paper, a W-band frequency-modulated continuous-wave (FM-CW) signal generator, a highly-sensitive quantum dot (QD) photo-detector, and a QD optical frequency comb laser (QD-CML) with optical pulsation were respectively demonstrated as possible candidates for photonic technologies. In the future, a real-time alert system for FOD on airport runways and railways will be further investigated and demonstrated using these advantageous photonic device technologies.

6. Acknowledgments

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7. References

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