Integrated Photonic/RF 40-Gb/s Burst-mode Optical Clock Recovery for Asynchronous Optical Packet Switching

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Abstract: An integrated 40-Gb/s burst-mode optical clock recovery circuit with nanosecond locking time is demonstrated. It has 643-fs RMS jitter. The integrated burst-mode optical clock recovery is also used to detect the envelope of 40-Gb/s RZ payloads with 3-ns rise time.

OCIS codes: (250.3140) Integrated optoelectronic circuits, (070.6020) Signal processing

1. Introduction

In asynchronous optical packet-switched networks, one key function is to recover the clock with nanosecond-order time from asynchronously arriving variable length packets. The fast clock recovery not only works as an important component in the burst-mode receiver to synchronize the receiver with every incoming packet [1], but also plays an important role in detecting the payload envelopes for optical label swapping technique when the label is serially located in front of the payload and encoded at a lower bit rate or different modulation formats from the payload [2]. Knowing the location of the payload without processing the bits in the payload is required by the optical label swapping networks to erase/rewrite the label. In order to avoid overhead, bit-synchronization must be as fast as several nanoseconds. Conventional phase-locked loop circuits require several ten microseconds to recover the clock. Self-pulsating distributed feedback lasers and Fabry-Perot filters have been applied for optical clock recovery (OCR) on a packet per packet basis but no reports about their application of payload envelope detection (PED) [3, 4].

We have previously demonstrated a 40-Gb/s OCR circuit using a traveling-wave electroabsorption modulator (TW-EAM)-based ring oscillator [5], which is shown schematically as the shadow block in Fig.1 (a). Optical 40-GHz recovered clock was achieved through simultaneously modulating an injected CW light by the recovered electrical clock within the same TW-EAM.

In this paper, we demonstrate for the first time an integrated burst-mode OCR circuit that recovers the clock from 40-Gb/s input optical RZ packets with several nanoseconds. Furthermore, we used the integrated OCR to detect the payload envelope of the input optical packets. We measured the characteristics of the recovered 40-GHz clock and the PED signal, including its root-mean-square (RMS) jitter and locking time.

2. Principle of operation

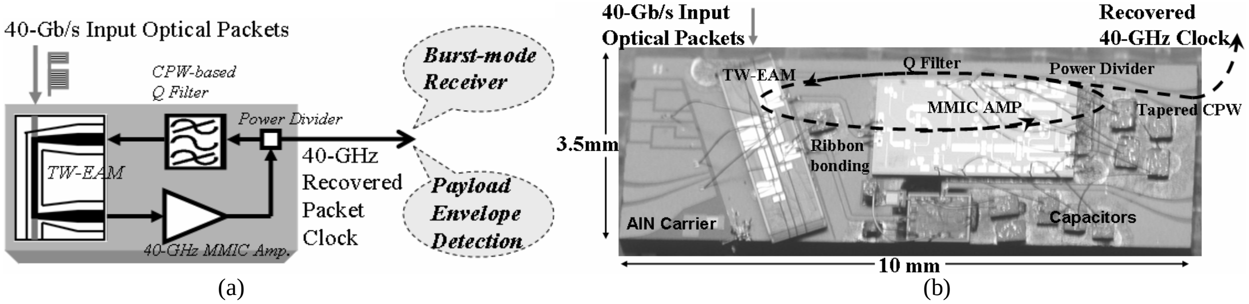
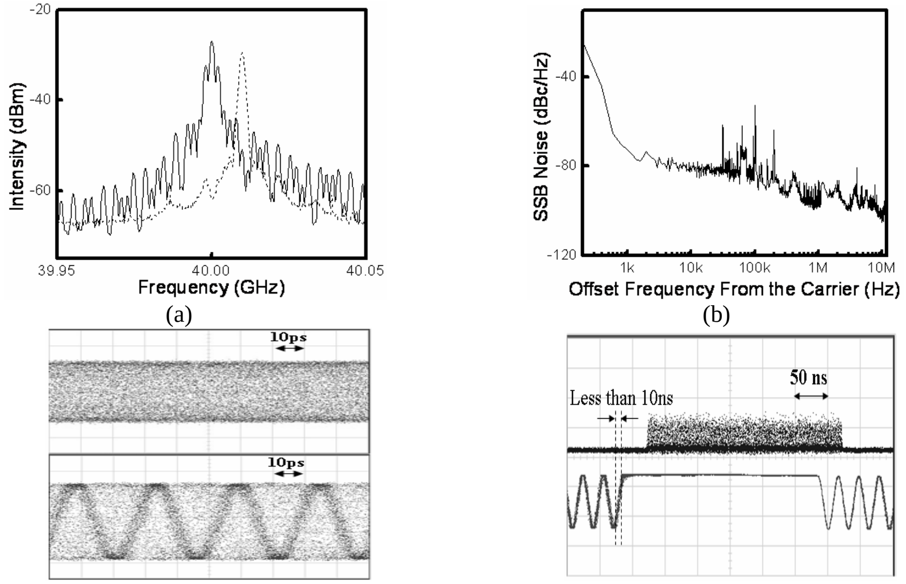


Fig. 1 (a) Configuration and (b) photo of the integrated 40-Gb/s burst-mode optical clock recovery circuit.

The integrated burst-mode OCR, shown in Fig.1 (b), uses an InP TW-EAM, a microwave monolithic IC (MMIC) GaAs amplifier, a coplanar waveguide (CPW)-based Q filter and power divider interconnected by several ribbon bonds to construct a 40-GHz self-oscillating ring oscillator, which is sit on an AlN carrier with the dimension of 3.5mm by 10mm. A tapered CPW line is used to couple out the recovered 40-GHz clock from the carrier. When the input optical signal contains a clock frequency within the ring oscillator's locking range, the ring oscillator can be injection locked through the photocurrent detected by the TW-EAM. Although a phase shifter was not employed in the oscillator, the phase tuning can be obtained through either adjusting the reverse bias voltage of the TW-EAM or tuning the gain of the MMIC amplifier. Our analytical modeling shows that lower Q factor will reduce the locking time but increase the jitter [6]. So, the Q filter with relatively low Q factor of 50 is designed and realized by creating capacitively coupled resonant section in the inner conductor. All the CPW lines and CPW-based components are designed to have 50-Ω characteristic impedance. A 36GHz-43GHz MMIC amplifier chip (XP1005, Mimix Broadband Co.) with 26dB gain was soldered on the AlN carrier and its gain can be adjusted through tuning its gate voltages. The whole loop length is about 12mm (corresponding to around 0.04-ns loop delay time) coarsely adjusted for 40-GHz operation. In the following experiments, we will demonstrate different characteristics of the integrated ring oscillator-based burst-mode OCR circuit operating at above or around the oscillation threshold of the ring oscillator. The characteristics enable the integrated OCR can work for both burst-mode receiver and PED function.

3. 40-Gb/s OCR operating at above the oscillation threshold of the ring oscillator

Optical 40-Gb/s RZ packets were generated by gating a 40-Gb/s 2^{31}-1 PRBS data stream through a $LiNbO_3$ modulator with 300-ns long payloads and 200-ns long guardbands. Without packets at the input, the integrated OCR is a free-running oscillator at a frequency of 40.02GHz, shown as the dashed curve in Fig.2 (a). When optical 40-Gb/s packets with 10-dBm average power were applied, the integrated OCR injection locked at the clock frequency shown as the solid curve in Fig.2 (a). The sidebands in the RF spectrum of the injection-locked OCR are generated from low frequency modulation characteristics of optical packets. In order to avoid these sidebands to affect the jitter evaluation of the OCR, we directly input the 40-Gb/s PRBS data instead of packets to the OCR. Fig.2 (b) depicts corresponding single sideband (SSB) noise spectrum of the main peak of the recovered 40-GHz clock. The RMS jitter of 643fs was obtained through integrating noise spectrum from offset frequency of 200Hz to 10MHz.



(a) (b)

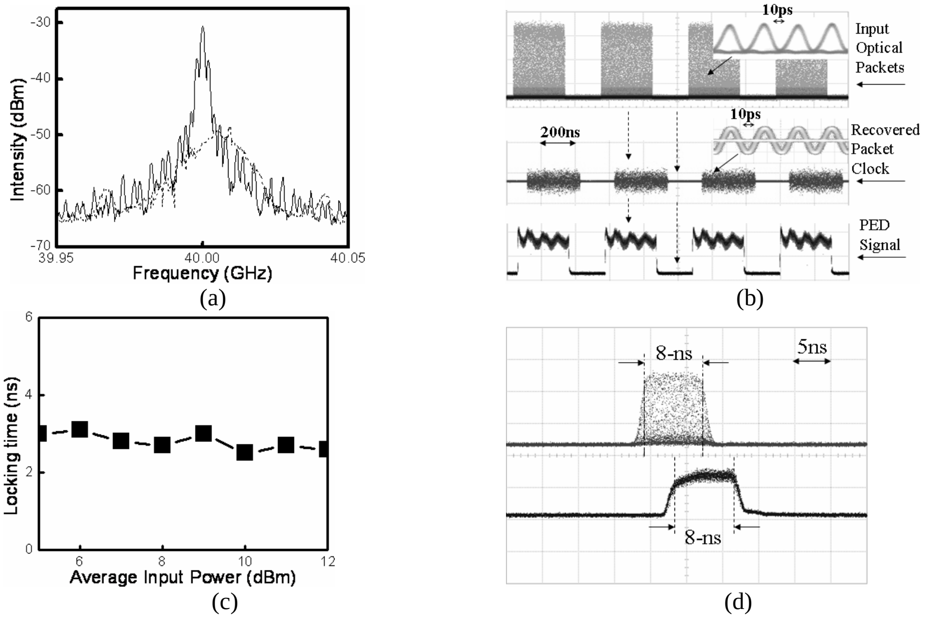
(c) (d)

Fig. 2 (a) RF spectra of free-running (dashed) and injection locking (solid) OCR; (b) SSB noise spectrum of 40-GHz recovered clock; (c) Oscilloscope traces of 40-GHz recovered clock before (upper) and after injection locking (lower); (d) Input optical packets (upper) and output IF signal from the mixer (lower).

Before injection locking, the OCR is not synchronized to the input clock which is used as the trigger signal of the sampling oscilloscope, shown as the upper waveform in Fig.2 (c). After injection locking, the recovered 40-GHz packet clock is shown as the lower waveform in Fig.2 (c). The overlap of synchronized and non-synchronized clock signals, corresponding to the payloads and guardbands, leads to smeared pictures due to the sampling nature of the oscilloscope. An RF mixer was used to measure the OCR's locking time: 40-GHz transmitter clock and 40-GHz recovered clock enter the LO and RF ports of the mixer, respectively. DC part of the output IF signal from the mixer indicates less than 10-ns locking time, shown as the lower waveform in Fig. 3(d). The low frequency component in the IF signal is due to the frequency difference between the input clock and the OCR's free-running oscillation.

4. 40-Gb/s OCR operating at around the oscillation threshold and its PED application

From above measurement, the integrated OCR's free-running oscillation always occurs in the guardbands between the payloads in the optical packets. In order to detect the payload envelope, the recovered clock is required to quickly appear at the beginning of the payloads and then rapidly vanish at the end of the payloads. So, we intentionally reduced the MMIC amplifier's gain to make the OCR operate at around oscillation threshold, shown as the dashed curve in Fig.3 (a). Then we applied 40-Gb/s optical packets to the OCR, which is shown as the top waveform in Fig.3 (b) and upper inset picture is its eye diagram. After further fine tuning the MMIC amplifier's gain and the reverse bias voltage of the TW-EAM, 40-GHz recovered clock was obtained shown as the solid curve in Fig.3 (a). Its corresponding oscilloscope trace is shown as the middle waveform in Fig.3 (b): the recovered clock corresponds to the payload and the zero level corresponds to the guardbands, respectively; middle inset picture in Fig.3 (b) shows the eye diagram of the 40-GHz recovered packet clock.



(a) (b) (c) (d)

Fig. 3 (a) RF spectra of free-running (dashed) at around oscillation threshold and injection locking OCR (solid); (b) Oscilloscope traces of the recovered 40-GHz packet clock (middle), the PED signal (bottom) detected from the input optical packets (top); (c) Locking time of the OCR against the average input power; (d) Oscilloscope traces of the PED signal (lower) detected from 8-ns long optical packets (upper).

The locking time of the 40-GHz recovered clock is evaluated through passing it through a Schottky envelope detector. The rise time of the output signal from the detector, i.e. PED signal, is regarded as the locking time of the recovered clock considering fast response of the detector. In the measurement, we inverted the PED signal by the oscilloscope for convenience because of inverted output from the envelope detector, shown as the bottom waveform in Fig.3 (b). The high level of the PED signal corresponds to the payload and the zero level corresponds to the guardbands, respectively. The locking time of the integrated OCR was directly obtained from the oscilloscope through measuring 90/10 rise time of the PED signal. We found its locking time keeps around 3ns for different average input power from 5dBm to 12dBm, shown as Fig.3 (c). When an 8-ns long optical packet was applied to the OCR, the corresponding PED signal recovered by the integrated OCR is shown as the lower waveform in Fig.3 (d). Compared with that of the OCR operating above oscillation threshold, faster locking time of the OCR operating at around oscillation threshold indicates less round-trip times are needed for building up.

5. Conclusion

Integrated 40-Gb/s burst-mode optical clock recovery is demonstrated to recover the clock within several nanoseconds. It has 643-fs RMS jitter. It is used to detect the payload envelope with 3-ns rise time, which is a key function required by label swapping technique. Schottky envelope detector will be integrated with the OCR in the future. This work is supported by LASOR award #W911NF-04-9-0001 under the DARPA/MTO DoD-N program.

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