Supermode Stabilized Coupled-Cavity 5- and 10-GHz Mode-Locked $Ti:Er:LiNbO_3$ Waveguide Lasers

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***Abstract*—By coupling the active laser cavity to a passive low-finesse Fabry–Perot resonator, supermode stabilization of mode-locked $Ti:Er:LiNbO_3$ waveguide lasers for 5- and 10-GHz pulse repetition rates with side mode suppression ratios of 60 and 55 dB has been achieved. The 10-GHz source emits pulses with a pulsewidth of 5.7 ps and a time–bandwidth product lower than 0.52 within an RF frequency tuning range of 3.2 MHz. The 5-GHz source has been used in a 2 × 5 Gbit/s soliton transmitter. In a back-to-back measurement, a Q-factor of 25.1 dB has been obtained. In soliton transmission experiments over 160 km on step-index fiber, an extrapolated bit error rate of $6 \cdot 10^{-17}$ has been measured. The passive cavity can serve also as a pulse repetition rate multiplier. Pulse repetition rate multiplication from 2.5 to 10 GHz has been demonstrated.**

***Index Terms*—Erbium doping, integrated optics, lithium niobate, mode-locked lasers, repetition rate multiplication, supermode stabilization, waveguide lasers.**

I. Introduction

OPTICAL pulse sources with high repetition rates are attractive devices for high-speed optical (soliton-type) transmitters. Therefore, frequency-modulated (FM)-type mode-locked $Ti:Er:LiNbO_3$ waveguide lasers with an integrated traveling wave phase modulator as a mode locker have been developed and investigated [1], [2]. These lasers are approximately 7 cm long [free spectral range (FSR) ≈1 GHz] to get sufficient pump absorption. In this way, diode-pumped and pigtailed devices with a slope efficiency of up to 14% have been demonstrated [2]. To get pulse repetition rates of up to 10 GHz, harmonic mode locking had to be used. However, harmonically mode-locked lasers usually emit more than one comb of longitudinal modes (called supermodes), causing high-frequency noise.

Several methods of supermode stabilization have been reported in the literature for fiber lasers with a very large number of supermodes [3]–[8]. As one approach, an intracavity Fabry–Perot filter with a high finesse (>50) has been successfully used to select one supermode [8]. In contrast to this transmission-type filter, we recently showed supermode stabilization by coupling the active laser cavity directly to a passive Fabry–Perot waveguide cavity with a low finesse [9], [10]. In this way, a reflection-type filter was realized on the same substrate material with the potential for full integration.

In this paper, we discuss the laser design and the characterization of the two realized coupled-cavity mode-locked $Ti:Er:LiNbO_3$ waveguide lasers in detail. We compare the two approaches of coupling the passive cavity to the front side or to the back side of the active laser cavity. The front-side coupled-cavity laser for a 5-GHz pulse repetition rate has been developed as a source for a soliton transmitter for step index (SI) fiber transmission with a pulsewidth of 15 ps [9]. The back-side coupled-cavity laser with a pulsewidth of 6 ps has been optimized for 10-Gbit/s soliton transmission (on dispersion-shifted fiber) [10]. The short pulsewidth even allows passive multiplexing; in this way, the generation of a 40-Gbit/s pulse train has been demonstrated [11].

The integrated Fabry–Perot filter can also be used for frequency multiplication, as has been demonstrated with fiber lasers [12]. We present the generation of a stable 10-GHz pulse train by a 5-GHz phase modulation. Moreover, up to fourfold multiplication has been achieved.

II. Laser Fabrication and Cavity Design

In order to fabricate the active laser cavities, Z-cut $LiNbO_3$ substrates have been doped by indiffusion of a 30-nm-thick layer of vacuum-deposited erbium at 1130 °C during 150 h. Afterwards, photolithographically-defined 7-μm-wide and 96-nm-thick Ti-stripes have been indiffused at 1060 °C during 8.5 h to form the 66-mm-long active waveguides.

Prior to the electrode fabrication, 0.9-μm-thick SiO_2-buffer layers have been vacuum deposited on the substrate surfaces to avoid excess losses. Three metal electrodes (Fig. 1) have been fabricated on the laser structures using photolithographic lift-off of a sandwich of 30-nm sputtered Ti and 120-nm sputtered Au. Subsequently, the traveling wave electrode was electroplated up to a thickness of 6 μm. The traveling wave phase modulators in the middle of the cavities are 25-mm-long symmetrical coplanar microstrip lines used for FM-type mode locking. On both ends of the active laser cavity, two lumped-type phase modulators have been integrated for push–pull operation to reduce spatial hole burning effects.

For supermode stabilization, a passive waveguide resonator has been glued to the active resonator at the front or back side, respectively (Fig. 1). The so-called 5-GHz coupled-cavity laser (upper diagram in Fig. 1) has been fabricated with a passive cavity of an FSR of 5 GHz; the 10-GHz coupled-cavity laser (lower diagram in Fig. 1) has a passive cavity with an FSR of 10 GHz.

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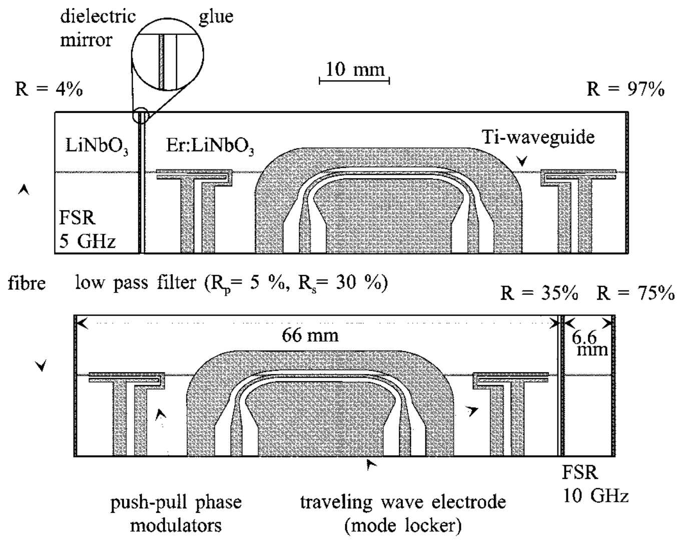

Fig. 1. Schematical diagram of the mode-locked Ti : Er : $LiNbO_3$ waveguide lasers with coupled cavity. Upper picture: 5-GHz coupled-cavity laser with a passive resonator (FSR = 5 GHz) at the front side. Lower picture: 10-GHz coupled-cavity laser with a passive resonator (FSR = 10 GHz) at the back side.

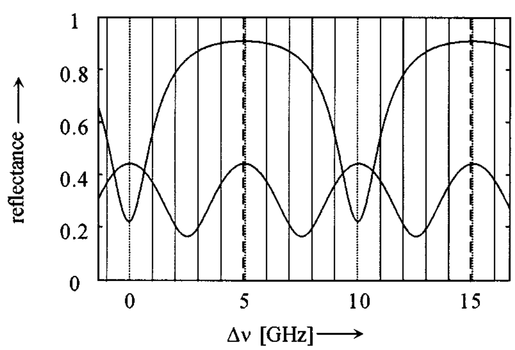

Fig. 2. Calculated reflectance of the passive cavities versus relative optical frequency at the wavelength 1550 nm. Upper curve: back-side coupled cavity with reflectivities of 35% and 75%. Lower curve: front-side coupled cavity with reflectivities of 30% and 4%. Dotted lines: stabilized supermode of the 5-GHz laser; dashed lines: stabilized supermode of the 10-GHz laser.

The mirrors of the active and passive cavities have been deposited directly onto the polished end faces by vacuum evaporation. The low-pass filter used for both samples consists of 15 layers of SiO_2 and TiO_2. It has been fabricated for a quarter-wave condition for 1900 nm, leading to a reflectivity at 1480-nm pump wavelength of about 5% and a reflectivity of 30% at 1550-nm wavelength. The mirrors at the back side are broad-band reflectors of 4 layers ($R = 35\%$), 8 layers ($R = 75\%$), and 12 layers ($R = 97\%$).

Supermode stabilization is done by the passive Fabry–Perot cavity serving as a laser mirror with a frequency-dependent reflectivity. If the FSR of the passive cavity is matched to the spacing of longitudinal modes representing a supermode, one supermode is selected by the reflectivity maxima. Therefore, a precise grinding and polishing step was necessary to get the right length of the passive resonators of a fifth and a tenth of the active resonator length, respectively. Fig. 2 presents the calculated reflectivities for the passive cavities of the 5-GHz and 10-GHz lasers.

Obviously, the larger the reflectivity difference for modes in the maxima and for the neighboring modes, the higher the stability of the selected supermode becomes. Such a supermode discrimination can be achieved with passive cavities of low finesse with a relatively low maximum reflectivity between the resonances (Fig. 2). Furthermore, it has to be taken into account that, for output power optimization, the laser should be operated with one mirror of high reflectivity and an ideal output coupling reflectivity of about 30% [13]. To get an easier mirror design allowing double-pass pumping, the laser output is extracted in the backwards direction. Consequently, the passive cavity can be used as an "output coupler" as was done in the 5-GHz laser (Fig. 1, upper diagram). The passive cavity with a low finesse of 2.3 fulfills the requirements of optimum output coupling and high supermode discrimination simultaneously. On the other hand, pump and signal light are guided through the passive cavity, causing additional losses.

If the passive cavity is used on the back side as in the 10-GHz laser (lower diagram of Fig. 1), a high reflectivity is necessary. This can be achieved in resonators of high finesse at the expense of a good supermode discrimination. Hence, for the back-side coupled-cavity laser, a passive cavity finesse of 4.3 has been chosen as a compromise between maximum output power (high finesse yielding high reflectivity) and best stability (low finesse).

The lasers have been pigtailed with the common branch of a fiber optic wavelength division multiplexer (WDM). They were packaged in an Al-housing including temperature stabilization, an optical isolator, and two fiber optic power splitters to get one output tap (1%) for monitoring and another one (9%) for deriving a control signal for feedback stabilization [2].

III. Supermode Stabilized Operation

A. Operation Conditions

The stability of mode-locked lasers in Fabry–Perot-type cavities suffers from spatial hole burning effects which degrade the low-frequency as well as the high-frequency stability. The holes in the population inversion are located at the cavity positions where the pulses are crossing each other ($n - 1$ positions for nth harmonic mode locking) [14]. Therefore, the (push–pull) phase modulators close to the waveguide ends are used to shift the intensity pattern back and forth to suppress these standing wave effects [15]. A push–pull modulation frequency of about 5 MHz and a modulation depth of 0.1 rad was sufficient to get rid of spatial hole burning effects.

In order to suppress relaxation spiking of the laser during mode locking, 9% of the laser output was detected and used for controlled pumping [2]. With a low-frequency (2-MHz bandwidth) stabilization unit, a correction component to the drive current of the pump laser diode is generated. It is possible to suppress the low-frequency noise by up to 42 dB.

For FM-type mode locking, the RF driver signal from a synthesizer has been boosted to an RF power of 26.5 dBm (10-GHz laser) and 29 dBm (5-GHz laser). Mode locking is achieved at 9.93 GHz (10-GHz laser) and 4.99 GHz (5-GHz laser), respectively. In contrast to fiber lasers, stable mode locking is possible without any active control of the optical cavity length [8].

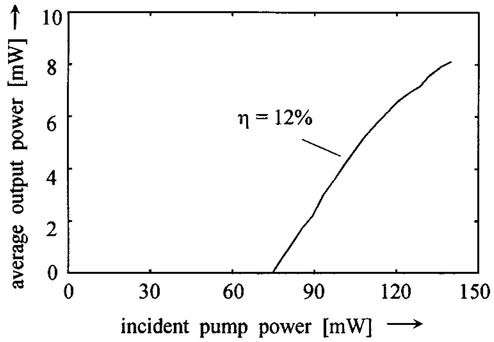

Fig. 3. Power characteristic of the 10-GHz mode-locked coupled-cavity laser.

B. Power Characteristics

The mode-locked lasers are pumped by a broad-band high-power laser diode with a central wavelength of 1480 nm. Up to 140 mW of pump power was available in the common branch of the WDM in front of the waveguide laser. Taking a coupling loss of 0.7 dB (measured at the 5 GHz laser) and a reflectivity for the pump wavelength of about 5% into account, a coupled pump power of up to 115 mW can be evaluated. Both mode-locked lasers emit for σ-polarized (TE) pumping in σ-polarization at the wavelength of 1562 nm. The average output power of the 10-GHz laser during mode locking is shown in Fig. 3. A threshold of 74 mW and a slope efficiency of 12% have been measured leading to a maximum average output power of more than 8 mW. In comparison with the single-cavity laser (with a back-side mirror of high reflectivity), the output power is reduced by 12%. For the 5-GHz laser, a maximum average output power of 6.3 mW has been measured.

C. Supermode Selection

To investigate the supermode stability, the output pulses have been detected by a photodiode with 19-GHz bandwidth and analyzed by an RF spectrum analyzer. In Fig. 4, the results for different mode-locked lasers are compared. In a single-cavity laser without supermode stabilization [Fig. 4(a)], strong supermode beat noise components with a frequency difference of the FSR (≈1 GHz) are visible. A side mode suppression ratio (SMSR) of only 8 dB has been measured.

The coupled-cavity lasers exhibit a drastically improved performance. In the RF spectrum of the 10-GHz laser [Fig. 4(b)], only small beat components at 1, 2, 9, and 11 GHz are appearing, which indicates that only the adjacent supermodes are not completely suppressed. However, the supermode stability of this laser with a SMSR of 55 dB is excellent. The RF spectrum of the 5-GHz coupled-cavity laser [Fig. 4(c)] is even better, as it is free of any supermode beat noise. The SMSR is larger than 60 dB, which is the dynamic range of the RF spectrum analyzer.

D. Pulse Properties and Detuning Characteristics

The laser emission has been investigated in more detail by measuring the autocorrelation of the optical pulses and the optical spectrum with a resolution of 0.015 nm. The results for both lasers are summarized in Table I.

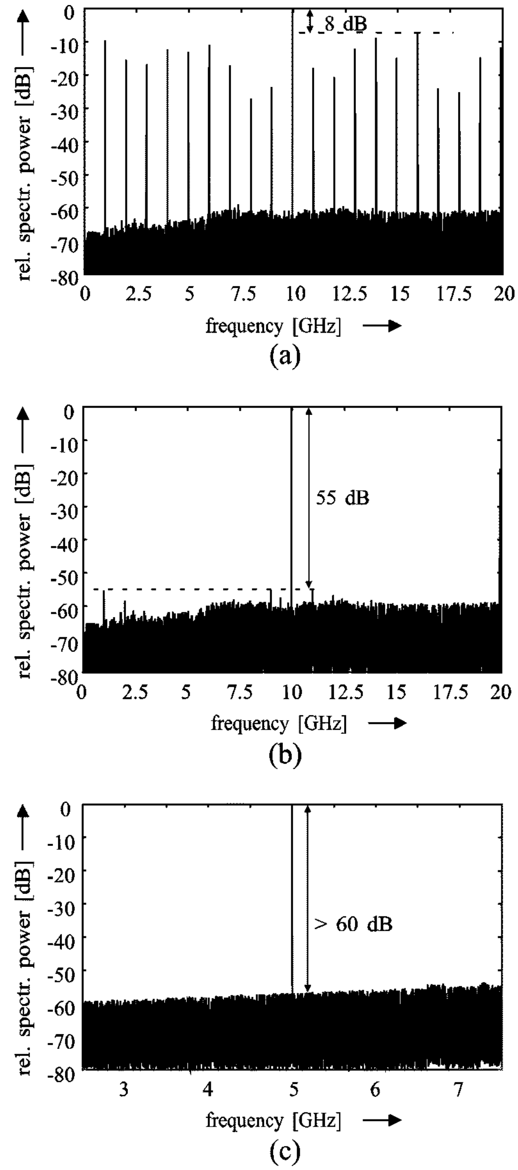

Fig. 4. RF spectrum of the output of three different mode-locked lasers. (a) Single-cavity laser at 10th harmonic mode locking. (b) A 10-GHz coupled-cavity laser. (c) A 5-GHz coupled-cavity laser. The resolution bandwidth is 10 kHz.

TABLE I
PULSE PROPERTIES OF THE COUPLED-CAVITY MODE-LOCKED LASERS

modelocked laser	τ	$\Delta\lambda$	$\tau \cdot \Delta\nu$
5 GHz laser	14.7 ps	0.32 nm	0.56
10 GHz laser	5.7 ps	0.64 nm	0.45

For the 5-GHz source, a pulsewidth of 14.7 ps has been measured. Together with the spectral bandwidth of 0.32 nm, a time–bandwidth product of 0.56 results. We assume that the comparatively large pulsewidth is a result of a small mismatch between the FSR of the passive cavity and the fifth harmonic of the FSR of the active cavity (= mode-locking frequency) of about 1%. Due to this mismatch, the periodic reflectivity (see the lower curve in Fig. 2) gets out of phase with the FSR of the active laser cavity. As a consequence, the reflectivity of the

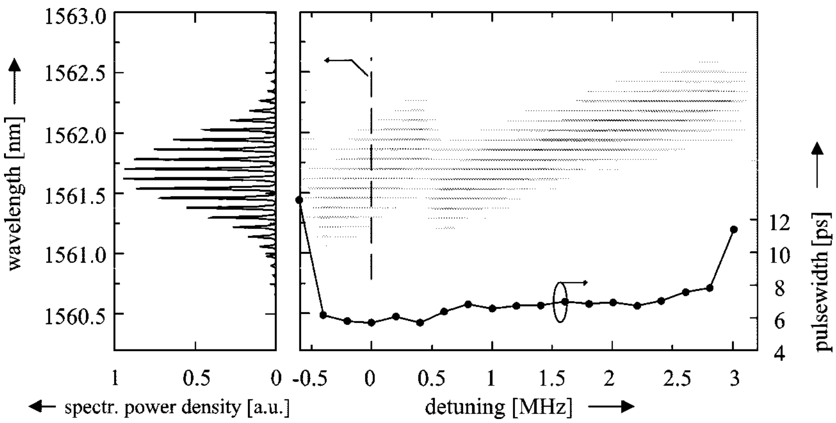

Fig. 5. Detuning characteristics of the 10-GHz coupled-cavity laser. Left-hand side: optical power density versus wavelength at the driver frequency of 9.9318 GHz (marked with the dashed vertical line). Right-hand side: Optical power density spectrum and pulsewidth versus RF driver frequency detuning.

longitudinal modes of one supermode is reduced at the wings of the optical spectrum, leading to a reduced optical bandwidth and, therefore, to an increased pulsewidth.

The investigation of the 10-GHz source has been performed in the whole frequency range of more than 3 MHz where stable mode locking is observed. For the frequency of 9.9318 GHz (set as 0 detuning) the smallest pulsewidth of 5.7 ps has been measured. Together with the spectral width of 0.64 nm, a time–bandwidth product of 0.45 results—indicating that the pulse is almost chirp-free, if a Gaussian pulse shape is assumed. The highly resolved optical spectrum, presented on the left-hand side of Fig. 5, shows the comb of longitudinal modes representing the selected supermode; the mode spacing is 0.081 nm. The stable emission of this spectrum confirms the excellent supermode stability.

From the literature, it is well known that FM mode-locked lasers can suffer from pulse phase instabilities [16]. The pulse train of the laser is synchronized either to the phase modulation maximum (called the positive mode) or to the phase modulation minimum (called the negative mode). According to modeling results [16], [17], the central wavelength shifts to a larger (smaller) wavelength by increasing the RF driver frequency for the positive (negative) mode, respectively.

Fig. 5 presents the spectral power density, measured in a total frequency range of 3.8 MHz. Between –0.4 and 2.8 MHz detuning, the central wavelength is rising with the RF frequency, which means that the laser is emitting in the positive mode. This result coincides with the observation of the laser pulses by a fast sampling oscilloscope. No jumps between interleaved pulse trains occurred in this frequency range. At a detuning of 0.5 MHz, the central wavelength shifts by 0.5 nm. By accurately analyzing the spectrum at this driver frequency with a Fabry–Perot spectrum analyzer, it was found that the laser emission jumps from one supermode to the neighboring one; the longitudinal modes displayed in Fig. 5 shift by one FSR of the active cavity (i.e., 0.008 nm). The pulsewidth varies only from 5.7 to 7.8 ps within the detuning range of –0.4 and 2.8 MHz; the time–bandwidth product remains below 0.52.

E. Bit Error Rate Measurement

Bit error rate (BER) measurements have been performed with the 5-GHz laser to investigate the stability of the coupled-cavity

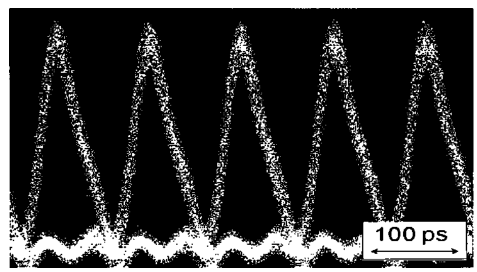

Fig. 6. Eye diagram of the 2 × 5 Gbit/s pulse train.

laser. The laser has been developed for a 2 × 5 Gbit/s soliton transmitter emitting pulses of alternating orthogonal polarizations. Therefore, the 5-GHz pulse train has been split by a 3-dB power divider, encoded separately, and multiplexed with orthogonal polarizations to a 10-Gbit/s signal [18]. The eye diagram of such a signal measured in a back-to-back configuration (modulated source and receiver only; without transmission line) indicates the low noise level of the pulse train (Fig. 6). By investigating the threshold voltage of the BER analyzer, a Q-factor (defined, e.g., in [19]) of 25.1 dB has been measured, leading to an extrapolated BER of $3 \cdot 10^{-73}$.

As soliton transmission over SI fiber without inline control requires longer pulses than delivered by the integrated source at a minimum time-bandwidth product, a bandpass filter has been used to increase the pulsewidth from 15 to 45 ps. Without clock recovery, it was possible to demonstrate extrapolated BER's of $6 \cdot 10^{-17}$ for soliton transmission on 160-km SI fiber with a 40-km amplifier spacing.

IV. Pulse Repetition Rate Multiplication

Using the higher order sidebands of the intracavity FM modulation, the pulse repetition rate of actively mode-locked lasers can be multiplied by an integral multiple q of the modulation frequency. Two different arrangements are possible. For rational harmonic mode locking, the cavity is modulated with a frequency f_m/q, where f_m/q is not an integral multiple of the active cavity FSR (mode-locking frequencies of the laser) but f_m is one. Therefore, longitudinal modes with a spacing of f_m are locked and the pulse repetition rate is multiplied by a factor of q [20]. In another scheme, an intracavity Fabry–Perot filter with

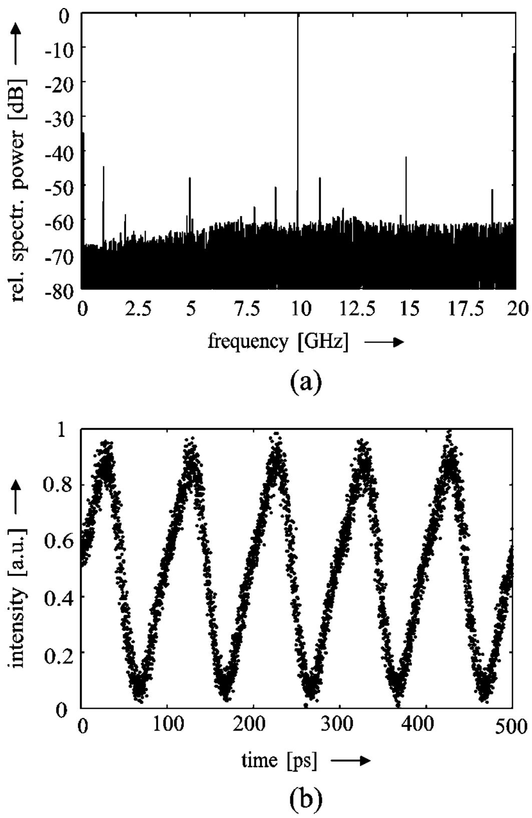

Fig. 7. (a) RF spectrum and (b) sampling oscilloscope trace of the pulse repetition rate doubled mode-locked laser.

an FSR of f_m is used to suppress the lower order FM sidebands (e.g., at f_m/q) [12].

Both schemes have been applied to the coupled-cavity 10-GHz mode-locked Ti : Er : $LiNbO_3$ waveguide laser. Pulse repetition rate multiplication (by factors of 2, 3, and 4) has been achieved at frequencies of 4.965, 3.310, and 2.483 GHz with 30 dBm of RF power fed to the traveling wave electrode of the 10-GHz laser; 5 GHz is a multiple of the active cavity FSR. Therefore, the second method is used for frequency multiplication with the passive cavity as an intracavity filter. Fig. 7 shows the RF spectrum and the pulse train of the 10-GHz laser operated by a 5-GHz phase modulation measured with a fast photodiode and a sampling scope. The 5-GHz RF component is 47 dB smaller than the signal at 10 GHz. The sampling oscilloscope trace indicates an excellent pulse stability. The results have been obtained with a significantly lower round-trip phase modulation of 0.23 rad (due to the σ-polarized laser emission) in comparison with published results for fiber lasers (2.4 rad) [12].

The driver frequencies of 3.3 and 2.5 GHz are not harmonics of 1 GHz (mode-locking frequencies of the active laser cavity). Therefore, mode locking with these frequencies corresponds to rational harmonic mode locking. The passive coupled cavity is used here—as before in the conventional mode-locked laser—for the supermode selection and stabilization. To prove the 10-GHz pulse generation at 3.3 and 2.5 GHz phase modulation, the autocorrelation of the laser output has been measured. The correlation traces for both modulation frequencies (see Fig. 8) show in both cases a 10-GHz pulse train. As expected

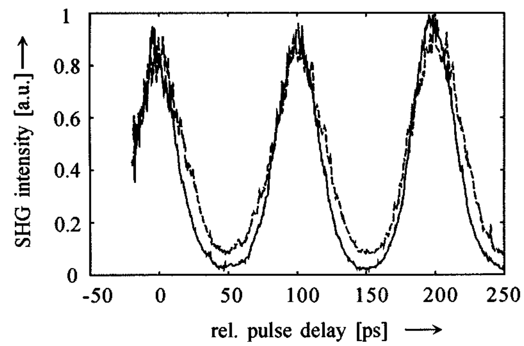

Fig. 8. Autocorrelation traces of the pulse train for a driver frequency of 3.31 GHz (solid line) and 2.48 GHz (dashed line).

from the theory given in [12], pulse phase instabilities of the 10 –GHz pulse train (that means jumping by 50 ps) occurred only for the 3.3-GHz and not for the 2.5- and 5-GHz modulation.

V. Conclusions

We have demonstrated coupled-cavity mode-locked Ti : Er : $LiNbO_3$ waveguide lasers for 5- and 10-GHz pulse repetition rates. Supermode stabilization with SMSR's of 55 and 60 dB has been achieved. The 10-GHz laser emits transform-limited pulses at a wavelength of 1562 nm with a pulsewidth of 5.7 ps. The frequency range for stable mode locking is 3.2 MHz. The 5-GHz laser with a larger pulsewidth of 14.7 ps has been used for transmission experiments. BER measurements prove the excellent pulse stability with extrapolated BER's of 10^{-73}.

Repetition frequency multiplication up to a factor of 4 is demonstrated from 2.5 to 10 GHz. This method can be used for generating pulse trains for high-capacity OTDM systems, e.g., synchronized pulse repetition rates in the 40-GHz range using a drive signal of only 10 GHz.

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