Looking for possible causes of loss, a TEM analysis was performed on the GaAs/InP interface. Fig. 4 shows a micrograph of the cross-section where it can be observed that the underside of the waveguide epilayer is not smooth. This observation corroborates with the well-known problem of obtaining high Al-containing epilayers with good surface morphology by MBE; the waviness of the GaAs in this case had most likely been caused by the surface roughness of the AlAs release layer. The roughness amplitude on the GaAs ranged from 2 to 14 nm and a simple slab calculation of surface scattering yields $\gamma \approx 1.8 \text{ dB/cm}$ per GaAs epilayer surface. The remaining loss, comparable to that of heteroepitaxially grown GaAs/GaAlAs/InP waveguides by OMCDV, could be attributed to further scattering centres caused by dust particles trapped at the interface; these particles would also be responsible for small distortions of the GaAs film and its misalignment with the InP.

Conclusions: Single-mode GaAs rib waveguides on an InP substrate have been successfully fabricated using epitaxial lift-off and standard processing after film transfer. Propagation losses lower than heteroepitaxially grown counterparts have been achieved without the incorporation of buffer layers. Surface scattering caused by roughness of the GaAs has been identified as one of the loss mechanisms in these waveguides. It is envisaged that smoother epilayers, grown for example by OMCDV, and improved cleanliness in the grating process will result in waveguides with lower propagation loss. The fabrication technique reported here can be extended to the fabrication of other devices based on lattice-mismatched components.

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References


PHOTON TIMING OTDR: A MULTIPHOTON BACKSCATTERED PULSE APPROACH

Indexing term: Measurement

Time-correlated photon counting with solid state detectors is of considerable interest for high resolution optical time-domain reflectometry (OTDR). Up to now, long measurement times were required. A new approach is described, yielding measurement times 50 times shorter and dynamic range enhanced by ± 20 dB.

High performance levels are attained by optical time domain reflectometers (OTDR) based on single-photon techniques employing avalanche photodiodes (APD). Commercial apparatus with about 300 ps resolution full width at half maximum (FWHM) i.e., 3 cm, is available. The APD bias voltage is pulsed above the breakdown for a short time, delayed by a controlled amount with respect to the laser pulse. A time window is then defined: only photons arriving within this time slot can trigger an avalanche current pulse. The OTDR trace is obtained by scanning the delay. This strategy has two drawbacks. The available resolution of the detector is not fully exploited, since the resolution of the OTDR measurement is determined by the gate pulse duration rather than by the inherent detector resolution. The measurement time is long, since the procedure is not efficient in the collection of the available information.

The first drawback can be avoided by using the time-correlated photon counting (TCP) technique. Resolutions of 50 ps FWHM, i.e., 0.5 cm, were obtained in our laboratory. The measurement time required is still long. A new approach, based on an accurate analysis of TCP, is presented. TCP with multiphoton backscattered pulses and an appropriate data analysis are employed. Dramatically reduced measurement times (by a factor of 50, i.e., down to a few minutes) and a remarkable improvement (± 20 dB) in the dynamic range at subcentimetre resolution are experimentally demonstrated.

The TCP technique consists of:

(a) measuring the arrival time of a backscattered photon, marked by the current pulse from the photodiode
(b) collecting a statistical histogram of many such measurements.

Gating of the photodiode is normally not employed. The time resolution of the detector (which can attain 20 ps) is fully exploited, but the data collection time is long. In fact, the available high-resolution time-sorters can process only the
first stop (photon) pulse following the start (laser) pulse. If a backscattered pulse contains more than one photon within the measurement time range, only the first is measured. The collected histogram represents the probability distribution of the first photon. The correct OTDR trace would be the probability distribution of a photon. The difference between the two is negligible only if the probability of multiple (two or more) photons $P_N$ is negligible with respect to that of just one photon $P_R$. This is obtained by attenuating the light, so that the total event probability $P_T$ (probability of one or more photons) be of the order of $10^{-5}$. In this case, it is easily shown (Poisson statistics of the backscattered photons) that $P_T \approx P_R$ and $P_N \approx (P_R)^2$. For instance, with $P_R = 0.05$ and a laser repetition rate of 10kHz, only 500 measurements per second are collected. For measuring with high resolution the Rayleigh scattering over moderate fibre lengths, measurement times of hours are necessary, as illustrated by the example in Fig. 1, OTDR trace.

By reducing the attenuation of the detected light, the data collection rate is strongly increased and the signal-to-background ratio is enhanced. Multiphoton backscattered pulses are, however, detected and the collected data are distorted. Fortunately, a correction equation makes it possible to derive the true distribution from TCPC data, recorded with significant $P_N$ (the number of laser pulses employed is the only additional information required). The computation routine is very simple. The correct probability for backscatter to arrive at a given time (i.e., from a given location in the fibre) is computed from the ratio (photon pulses recorded at that time)/employed laser pulses—photon pulses recorded at preceding times.

We have performed OTDR measurements by using this procedure. Data were collected for 2 min, by using the full power of the laser diode (Opto Electronics PPI.30K emitting at 904 nm pulses with 80 ps FWHM and 30 kHz repetition rate). This corresponds to almost unity $P_R$ for the first fibre and the connectors, so that the fibre after the connector could not be measured. A separate 60 min measurement was therefore performed. The detector operation was inhibited for the time interval corresponding to the first fibre and connector by switching the bias voltage below the breakdown. A section of 1-2 m just after the connector is excluded from this measurement. This arises since:

(i) at this level of detected intensity, the inhibited interval must include the connector reflection
(ii) the voltage transition from off-state (below the breakdown voltage) to on-state (a 10 V swing) takes 10 ns

A third measurement was necessary, in order to complete the OTDR trace. The detector was enabled just before the connector reflection and the light coupled to the fibre was attenuated. If the full laser power were used, the connector reflection would be enough to obtain a unity $P_R$, and the following fibre would still be unmeasurable.

The time required for obtaining the PTDR trace in this section can be minimised by optimising the coupled light power. If it is made too high, the connector reflection masks the backscatter from the subsequent fibre. At low power, the backscatter is reduced, and the measurement time is increased. By exploiting the Poisson statistics, one easily finds the optimum value for $P_R$. In the particular case of a small (Rayleigh) scattering after a big reflection, the optimum is $P_R = 0.63$.

The complete OTDR trace was obtained by merging the three measurements: it is shown in Fig. 1 trace b. The total measurement time is 17 min (to be compared with the 14 h required for the straight TCPC measurement in trace a). Much lower statistical dispersion of the data points, in particular for the second fibre section is observed. The dynamic range is enhanced, as illustrated by the ratio of the Rayleigh scattering level to the dark level after the fibre end. An accurate comparison of the OTDR traces in the two measurements does not reveal any detectable difference in the scattering levels. It is therefore verified that the correction procedure does not introduce systematic errors and, in particular, that the simple correction routine yields reliable results.

In order to evaluate the attainable dynamic range, we performed other PTDR measurements on the same fibre. The connector was made lossier. The result of a 30 min measurement in this condition is shown in Fig. 2. Note that although the Rayleigh scattering from the second fibre is reduced by about 35 dB, it is still better resolved from the dark level with respect to the measurement of Fig. 1a.

In summary, the multiphoton backscattered pulse approach to photon counting OTDR offers remarkable advantages. Accurate measurements with subcentimetre resolution and improved dynamic range are obtained in fairly short times, suitable for practical applications.

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References
IMPROVED ALLAN VARIANCE REAL-TIME PROCESSING SYSTEM TO MEASURE FREQUENCY TRACKING ERROR OF HETEROGENEOUS PHASE-LOCKED LOOPS

Indexing terms: Optical communications, Phase-locked loop

The performance of an Allan variance measuring system was drastically improved by employing time interval analysis incorporating a beat frequency method. It was used to evaluate the performance of a heterodyne optical phase-locked loop with a very low optical frequency tracking error of 0.4 MHz at the integration time of 70s. Advantages of the system are precise measurement for highly stable frequency sources with good reproducibility and simple structure.

Allan variance is a popular and important measure of the frequency stability of frequency sources. It can also be used to evaluate the performance of phase-locked loops in the time domain. To measure the stability of the optical frequency of a heterodyne optical phase-locked loop, we have demonstrated an Allan variance real-time processing system (ARPS), which employs the direct frequency counting method. In this system, the frequency of the source under measurement is down-converted to a countable frequency of a signal generator by a photo-diode and/or a double-balanced mixer (DBM) or frequency dividers. The performance of the ARPS was high enough to measure the frequency stabilities of LDs under stabilised and free-running conditions. Its resolution was limited by one count ambiguity during a sampling period, which means that the ARPS cannot resolve the frequency fluctuations smaller than 1 Hz in a sampling period. To overcome this restriction, we have developed a novel ARPS employing the time interval analysis method.

The optical frequency tracking performance of a heterodyne optical phase-locked loop with the phase error of 0.1 rad could be successfully evaluated by this novel system.

Fig. 1 shows the new ARPS. The frequency under test \( f_0 \) is down-converted to a lower frequency so that the final beat frequency \( f' \leq f_0 \), where \( f' \) is the frequency of the time base. Then the sinusoidal signals with the frequencies of \( f_0 \) and \( f_0' \) are converted to TTL level digital signals by zero crossing detectors (ZCD), which are high speed voltage comparators. The number of pulses generated by the time base signal is continuously counted by a 32-bit counter, which consisted of four 8-bit TTL counters. Each digital signal corresponding to \( f_0' \) generates two timing pulses at the same time, i.e., one is the interrupt signal to the personal computer and the other is the latch enable signal to the 32-bit data latch. From these timing signal, the 32-bit data latch latches the value of the 32-bit non-stop counter, and the computer reads the latched value through two 16-bit data buffers and a parallel interface board as soon as it receives the interrupt signal. By this operation, the computer can collect the number of pulses corresponding to the frequency of the time base during each period of \( f_0' \) without any dead time for measurement. The integration time, \( \tau \), can be determined by \( m/\tau_0 \), where \( m \) is a positive integer selected by the software program. The minimum measurable integration time is \( 1/\tau_0 \). The maximum distinguishable counting value is \( 2^m \) because the value of the counter is zero when the number of counters reaches \( 2^m \).

The condition of \( 2^m (\tau_0/\tau) > 1 \) is therefore required. Timing and gating circuits, the counter, the data latch and the data buffer were constructed using commercial TTL logic ICs. The maximum operating frequency of the system was about 30 MHz. The total required sample number \( N \) for each \( \tau \) to be measured can be selected using software, and the Allan variance \( \sigma^2(\tau) \) can be calculated using the collected data and the equation

\[
\sigma^2(\tau) = \left( 2 \sum_{i=1}^{N} \left( \frac{1}{N} - \frac{1}{N-1} \right) \left( \frac{1}{\tau} \sum_{j=1}^{N} \left( y_j - \bar{y} \right)^2 \right) \right)
\]

where \( y_j \) is the collected data for the \( j \)th sampling period. The Allan variance of the oscillators 1 and 2 used for the time base and the frequency down conversion of \( f_0' \) have to be higher than that of the device under test. If we ignore the effects on the measurement of instabilities in the oscillators 1 and 2, the measurement limit is determined by one count ambiguity of the time base signal during a sampling period and is given by

\[
\sigma^2_{\text{amb}}(\tau) = \left( \frac{1}{\tau} \sum_{j=1}^{N} \left( y_j - \bar{y} \right)^2 \right)
\]

Considering that the measurement limit of the previous ARPS was given by \( \left( \tau_0/\tau \right)^{m/2n} \), the measurement limit of the new ARPS is improved by a factor of \( \tau_0^2/\tau^2 \). The Allan variance of a higher stable frequency source can be measured by increasing this factor.

Precise frequency tracking between two LDs could be achieved by a heterodyne optical phase-locked loop (OPPLL), on which experiments have been carried out using two confocal Fabry-Perot cavity coupled LDs with spectral linewidths less than 10 kHz and wavelengths of 0.83 μm. The optical frequency tracking error of the heterodyne OPPLL was measured by the new ARPS. A measured result is shown by the closed circles (B) in Fig. 2, where \( f_0' \) was the optical frequency of the LDs used in the OPPLL experiment. The broken curve A and the solid line C in Fig. 2 are the theoretical measurement limits for the previous ARPS and the new ARPS, respectively.

In this measurement, \( \tau_0' \) and \( \tau_0 \) were 5 MHz and 1 kHz, respectively. The line C was determined with these values and eqn. 2. From the measurements we find that the minimum optical frequency tracking error was 0.4 MHz at \( \tau = 70s \), which is the lowest value among the published data. Such a stable phase-locked laser heterodyne signal could not be evaluated in the time domain with the previous ARPS as can be seen by comparing the experimental result B with the curve A in Fig. 2. To confirm the reproducibility of the measurement, the Allan variance of a signal was repeatedly measured more than 10 times, and the results showed very good reproducibility.

In summary, a novel Allan variance real-time processing system with high performance and simple structure was made with commercial TTL logic ICs, a popular 16-bit personal computer and some analogue circuits. This system could be...