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ULTRA-STABLE FIBER-OPTIC REFERENCE DISTRIBUTION FOR SwissFEL C-BAND LINACS BASED ON S-BAND RADIO-OVER-FIBER LINKS AND FREQUENCY DOUBLER / POWER AMPLIFIERS

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Abstract

The reference distribution for the SwissFEL accelerator is based on ultra-stable Libera Sync 3 fiber-optic links operating at 3 GHz with <2.4 fs added timing jitter. While s-band injector RF stations are directly supplied with these actively stabilized reference signals at 2.9988 GHz, the same 3 GHz optical links are used to transmit reference signals at 2.856 GHz (half c-band frequency) to the c-band LINACs, combined with a frequency doubler-amplifier at the link end. A novel zero AM/PM-conversion frequency doubler and an amplitude-/phase-controlled power amplifier have been implemented in a compact 1HU 19inch unit. Key design concepts and measurement results will be presented. It will be shown that this inexpensive doubler-amplifier system adds only insignificant jitter and drift to the transmitted reference signals. As the same actively stabilized 3 GHz links can be used for s- and c- band RF stations, development of a more expensive 6 GHz fiber-optic link could be avoided. A higher quantity of the same link type can thus be manufactured and the number of spares is reduced as only one link type is utilized for the SwissFEL injector and LINAC RF reference signals.

SwissFEL C-BAND REFERENCE DISTRIBUTION

The concept of the reference distribution for the SwissFEL accelerator RF stations and first performance measurements of the group delay stabilized Instrumentation Technologies Libera Sync 3 (3 GHz) prototype fiber-optic links have been presented in [1]. It is based on using 3 GHz radio-over-fiber links for distributing s-band (2.9988 GHz) as well as c-band (5.712 GHz) reference signals. For the c-band links the basic idea is not to transmit the c-band frequency itself but half of it (2.856 GHz) by means of a 3 GHz Libera Sync 3 link and then double and ampli-fy the transmitted signal frequency at the end of the link (Fig. 1). So we can use the same links for both s-band and c-band stations, which saves development and production costs for the fiber-optic links and simplifies testing and inventory.

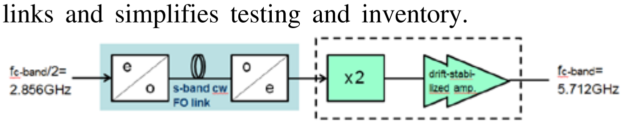

Figure 1: Concept of the radio-over-fiber based c-band link for the SwissFEL RF reference distribution. Dashed: frequency doubler / power amplifier. The timing jitter and gain / timing drift performance of the actual Libera Sync 3 link used in SwissFEL is shown in Figs. 2 and 3.

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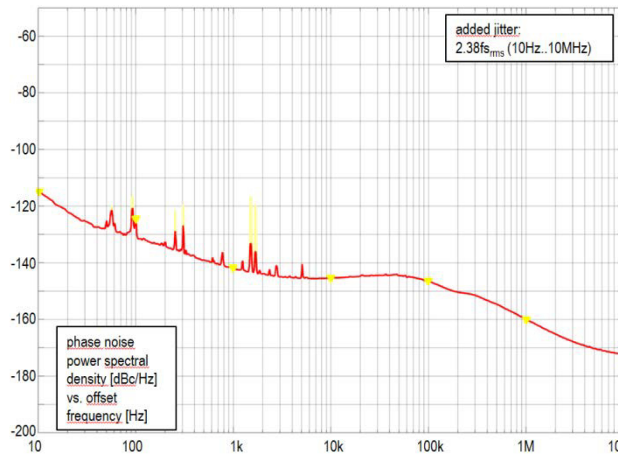

Figure 2: Libera Sync 3 fiber-optic link Added jitter at 2.9988 GHz for 500 m link span (standard SM fiber).

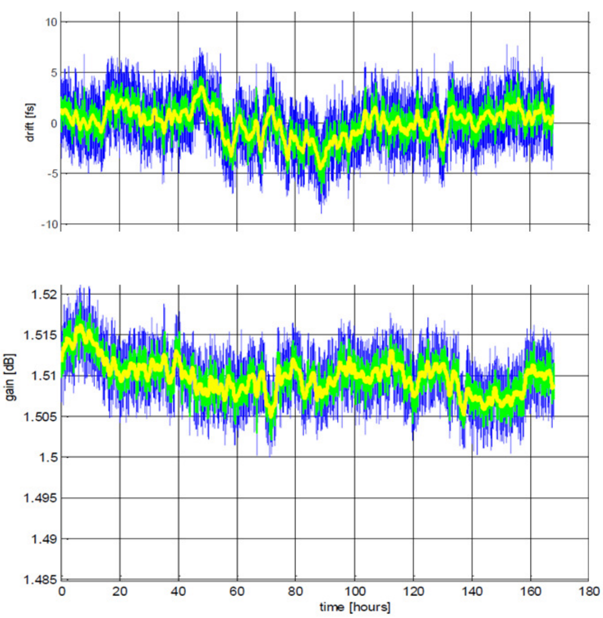

Figure 3: Libera Sync 3 drift measurement at 2.9988 GHz. Lower: Timing drift over 7 days: 11.9 fs_{p-p} (2.2 min avg.), 8.2 fs_{p-p} (1 h avg.), 2.6 fs_{rms}. Upper: Gain variation over 7 days, 0.017 dB_{p-p} (2.2 min avg.), 0.011 dB_{p-p} (1 h avg.).

As no frequency doubler / power amplifiers with the desired performance (particularly low phase drift and at the same time low jitter at high output power) are available on the market, such a device has been developed at PSI.

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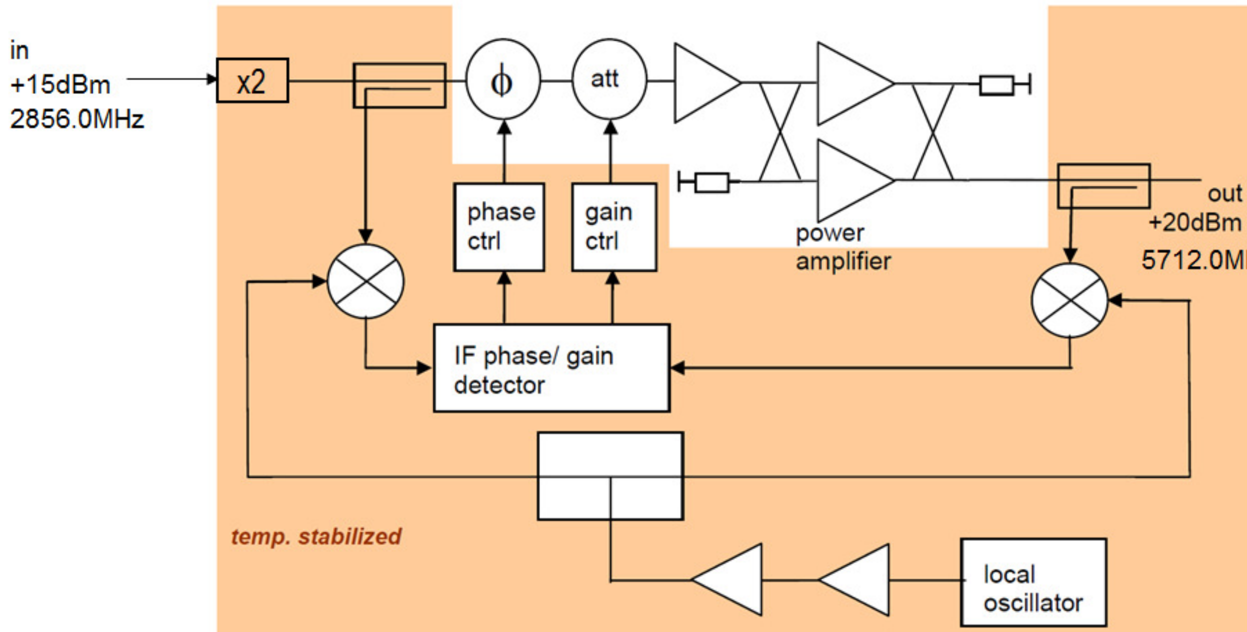

Figure 4: Block diagram of the frequency doubler / power amplifier.

3 GHz TO 6 GHz FREQUENCY DOUBLER / POWER AMPLIFIER DESIGN

The frequency doubler / power amplifier basically consists of two parts: a low jitter and low drift frequency doubler as well as a low drift and low jitter power amplifier (Fig. 4). The goal is to add virtually no jitter and a maximum drift of approximately 20 fs_{pp}.

Frequency Doubler

Commercially available frequency doublers are based on full wave bridge switching rectifier topologies. This is a relatively ideal topology regarding AM/PM conversion, which is considered the primary source of timing drift, furthermore Schottky diodes used in such devices yield low parasitic delay variations and added noise [2,3].

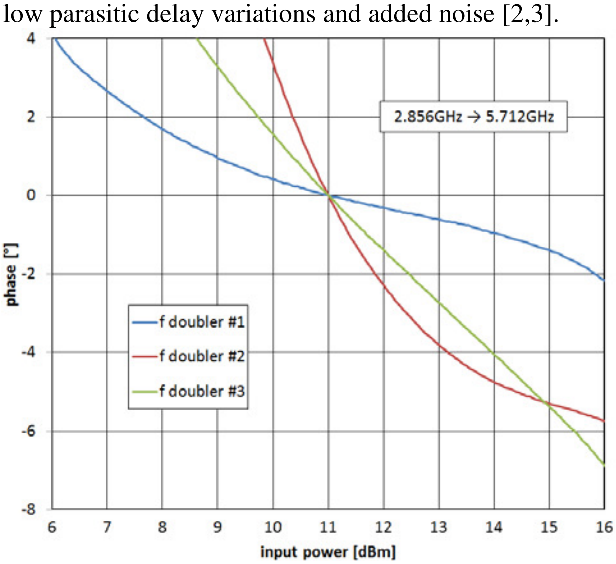

Figure 5: AM/PM conversion of commercial high performance frequency doublers.

Figure 5 shows the measured AMs ensitivity of three commercial high performance frequency doublers. The conversion loss of these doublers is approximately 10..12 dB. The AM/PM conversion coefficient varies between -50 m°/ 0.1 dB and -150 m°/ 0.1 dB (≈ -25.. -75 fs/ 0.1 dB) for realistic input power values. The frequency doubler with the lowest AM/PM conversion would al-ready eat-up the drift budget and leave no margin for the power amplifier, cables. To avoid this, a new doubler with optimized drift performance has been designed. The core of this new circuit is a double balanced mixer, which is a Schottky diode switching multiplier very similar to a full wave bridge rectifier but with two diodes reversed and two inputs instead of one. We split the input power and distribute it approximately equally to the two input ports of this doubler (mixer RF and IF ports), whereas the 2nd harmonic appears at the LO port (Fig. 6). The key idea is to vary the phase between the two input signals to active-ly compensate parasitic and unbalancing effects until the AM/PM conversion of the 2nd harmonic at the output vanishes. Figure 7 shows such an optimization. The conversion loss of the optimized doubler is approximately 16 dB. The optimum has been chosen such that it occurs at the maximum available input power. This yields maxi-mum output power of the doubler. The frequency doubler / amplifier unit has a switchable calibration output which allows adjustment of the doubler input port phase differ-ence by means of an electronically variable integrated phase shifter.

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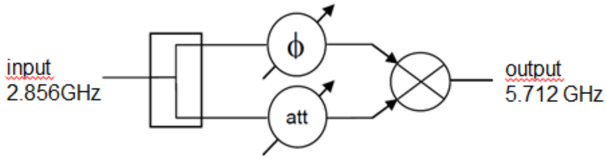

Figure 6: Core of the new frequency doubler.

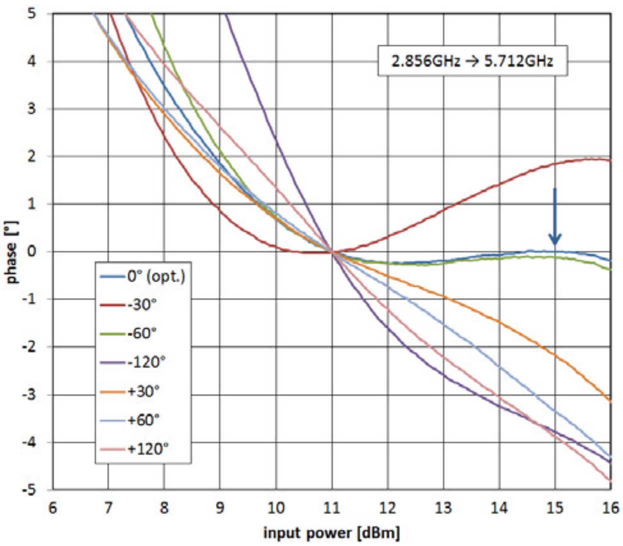

Figure 7: Optimized frequency doubler with virtually no AM/PM conversion (Marki M1-0310LEZ1 mixer based). Arrow: operating point.

The curves in Figs. 5 and 7 have been measured with a Keysight N5224A vector network analyzer (calibrated converter measurements with embedded LO).

Power Amplifier

The power amplifier's transfer function (gain and phase) is stabilized for the operating frequency of 5.712 GHz to minimize drift, using a two-loop controller (see Fig. 4). The key component of this controller is the well-known Analog Devices AD8302 gain / phase detector. The whole amplifier PCB is temperature stabilized to a few mK. Actually the detector part only is critical regard-ing temperature, as depicted in Fig. 4. InGaP HBT based active devices have been used for low phase noise. The output stage is a balanced configuration, which has some advantages over single ended as e.g. increased output power, better output match and reliability.

Gain / Phase Detector for Power Amplifier Stabilization

The following setup has been used for the AM sensitivity characterization of the AD8302 phase detector and find an appropriate operating frequency: A signal generator is modulating the injection current of a laser diode with a sinusoid (Mitsubishi 1550nm coaxial pigtailed DFB LD), whose output power is equally split to two channels of a remote controlled multichannel MEMS-based variable optical attenuator. The outputs of these attenuator channels are detected by two optical receivers (Discovery DSC50S lab buddies, operated with optical power that yields nearly zero AM/PM conversion), the phase difference of which is measured by the DUT (AD8302 gain/phase detector). The amplitude of one channel (one of the phase detector inputs) has been varied using one of the variable optical attenuator channels. Fig. 8 shows the measured sensitivity curves. These measurements reveal that the phase measurement should be done at a frequency of around 300..500 MHz for minimum AM sensitivity. It has been shown in [1] that this detector has a pp stability of a few fs over a day if it is stabilized within a few mK, even at the less convenient frequency of 3 GHz. If the 3 GHz input signal is downconverted to a few 100s of MHz and the same time the AM at the phase detector inputs can be minimized, which further reduces the effect of the remaining low AM sensitivity, a temperature stabilized AD8302 can well measure sub-10 fs_{pp} drifts over a day or longer in a carefully built setup (shielded against air flow, stabilized supply voltages, symmetric low drift cabling). The stability of the Libera Sync 3 link's input signal is better than 0.1 dB and its gain is extremely stable (see Fig. 2), which means that the frequency doubler (roughly constant conversion loss) hardly exhibits output power variations above 0.1 dB. The output signal of the power amplifier is stabilized by means of an in-loop variable microwave attenuator. Therefore the phase detector input amplitude variations will always stay below 0.1dB (stable LO power).

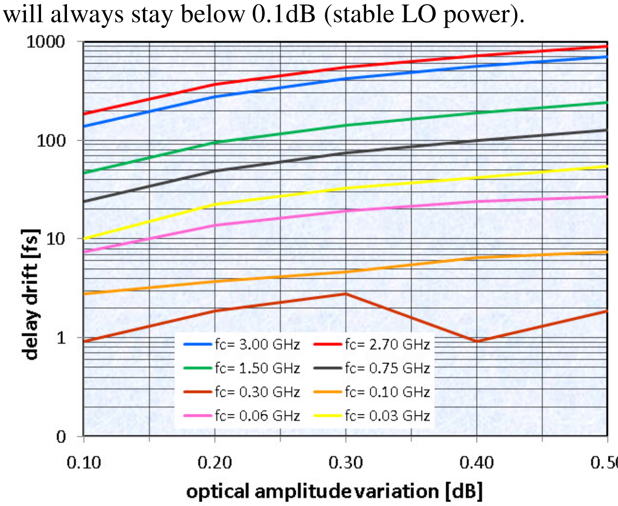

Figure 8: Frequency dependence of the AD8302 gain / phase detector AM/PM conversion, measured with a virtually AM/PM-conversion-free optical attenuator-based setup. Note that $\Delta P_{RF} = 2\Delta P_{opt}$. Resolution: a few fs.

PROTOTYPE MEASUREMENTS

A prototype frequency doubler / power amplifier has been developed and some first characterization has been done. More detailed measurements will follow later. The internally shielded and temperature stabilized 19' unit is quite compact (Fig. 9) and can be controlled via LAN interface. Later a small terminal on the front panel will be added for local control. Figs. 10 and 11 show jitter and drift measurements of the prototype unit. The latter has been done in the SwissFEL test injector laser hutch (temperature and humidity variations during this measurement were 0.3 °C and 3 %RH, respectively).

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Figure 9: Fabricated frequency doubler / power amplifier prototype (19", 1HU).

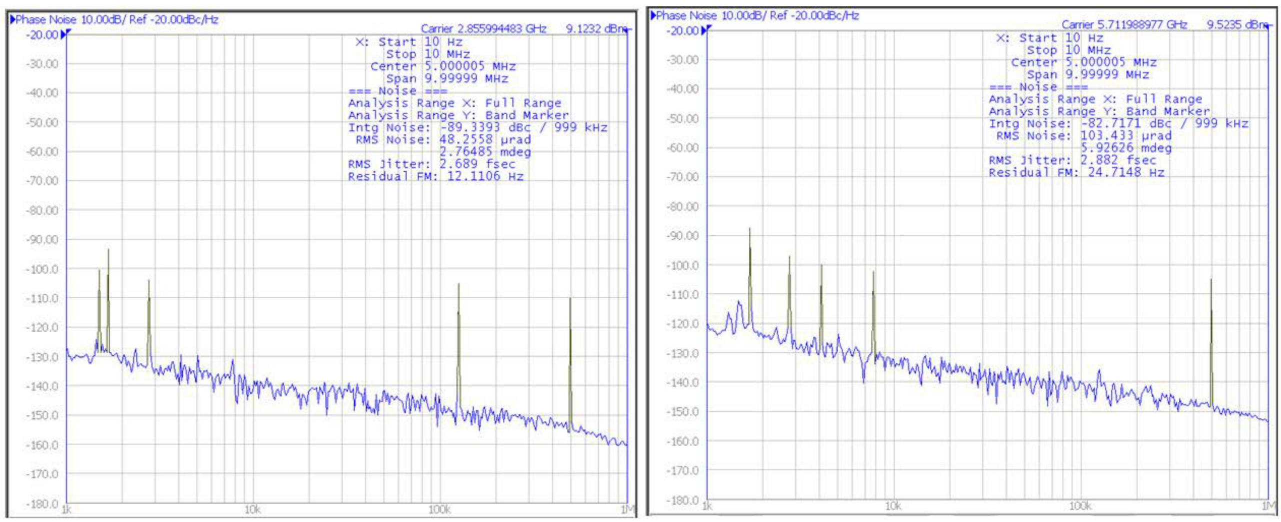

Figure 10: Phase noise / jitter measurement of the fabricated frequency doubler / power amplifier using an Agilent 5052B SSA. Left: Input phase noise spectrum / timing jitter. Right: Output phase noise spectrum / timing jitter. The phase noise is approximately 6dB higher than at the input (ideal frequency doubler). The added jitter of the frequency doubler / amplifier unit is approximately 1 fs in the critical range (1 kHz..1 MHz). The source was a Laurin reference generator.

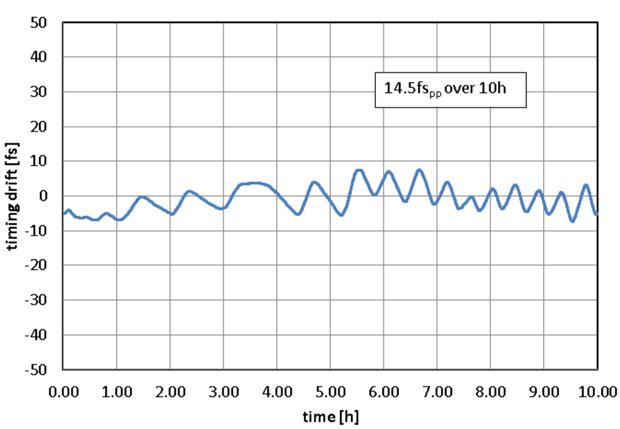

Figure 11: Timing drift measurement (avg. over 15min.) of the first frequency doubler / power amplifier prototype over 10h with not yet optimized temperature controller.

There was no time for extensive long term measurements yet but a first drift measurement shows the potential of the doubler / power amplifier' long term stability (Fig. 11). During this first drift measurement the lab air condition produced pronounced ringing in the relative humidity of $\Delta RH \approx 3$ % (SwissFEL sync room ΔRH specification is <2 %), which is exactly reproduced in the drift curve. Nevertheless the pp drift over 10 h was below 15 fs with potential for <10 fs after further optimization.

CONCLUSION

A frequency doubler / power amplifier unit for converting a 3 GHz radio-over-fiber link to a c-band link has been developed. Details on its design and first prototype measurements were presented. In combination with Instrumentation Technologies Libera Sync 3 3 GHz fiber-optic link the unit will be used to distribute c-band reference signals (5.712 GHz) in the SwissFEL facility. It adds only minor jitter and drift (potential for sub-10 f_{pp} drift) to the reference signals.

ACKNOWLEDGMENT

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