Frequency Combs

Compact, robust, high-end ... and convenient

Laser Reference

High-resolution Spectroscopy

Optical Clocks

Microwave Generation

Dual-comb Spectroscopy

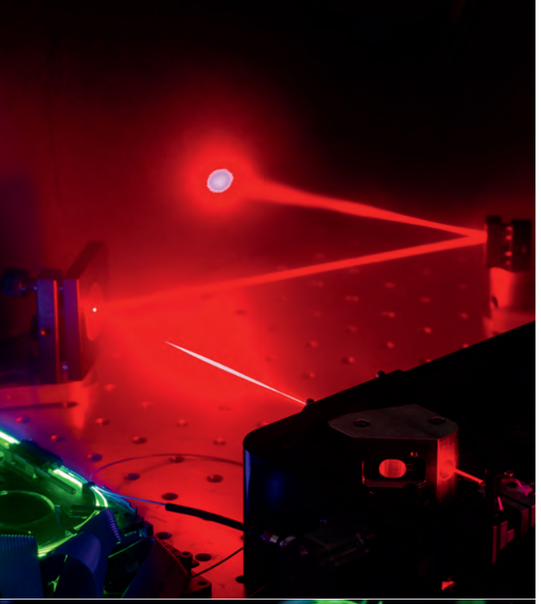
Direct Frequency Comb Spectroscopy

Interferometry

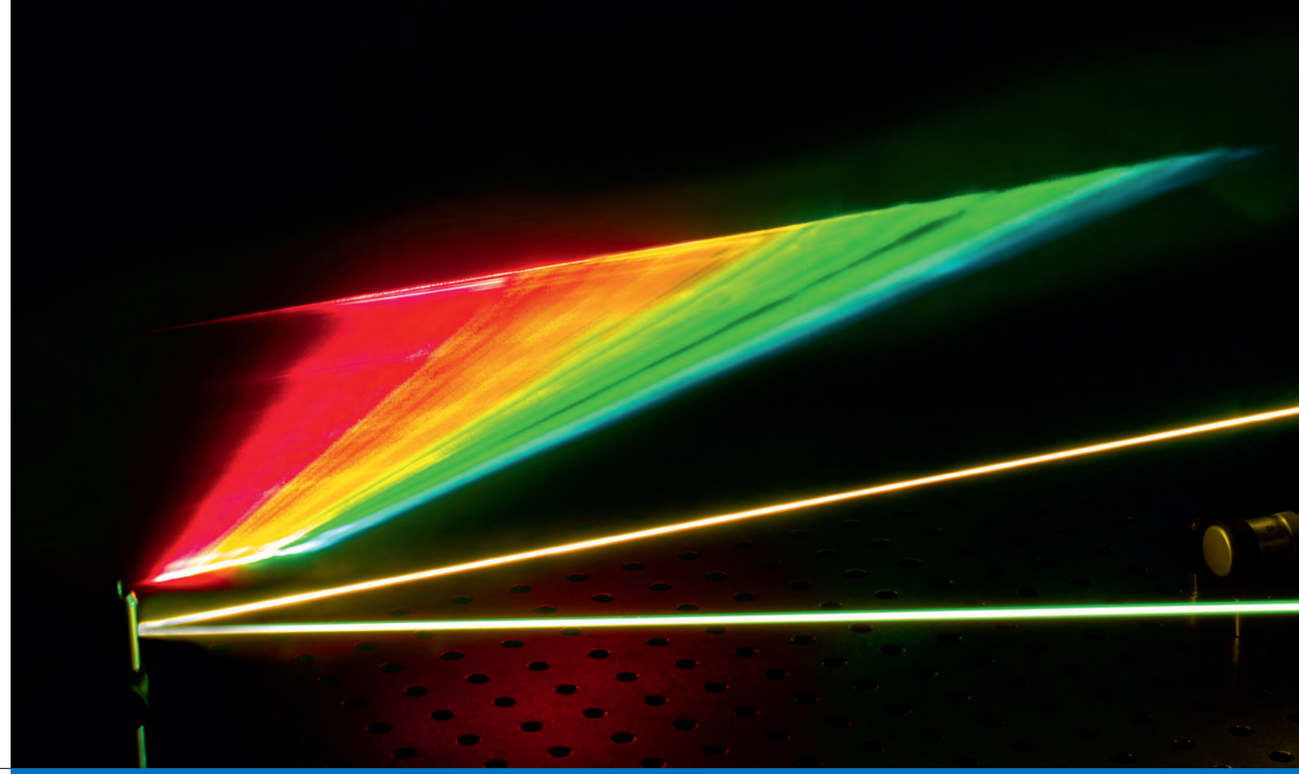
Transportable AMO Systems

Quantum Computing

TOPTICA PHOTONICS



Contents



Difference Frequency Comb (DFC)

Compact, robust, high-end ... and convenient

TOPTICA's Difference Frequency Comb (DFC) is a compact, robust, high-end solution featuring turn-key operation in a 19 inch format. All driving and locking electronics for RF references are integrated into the robust 19-inch housing of the Erbium fiber based frequency comb DFC CORE +. It features 4 or optionally 8 intrinsically offset-free outputs at 1560 nm which can be equipped with wavelength extension modules (DFC EXT) converting the comb light to any wavelength between 420 nm and 2200 nm.

The convenient user interface offers time-saving remote control of the frequency comb laser system and all its accessories like counter, spectrum analyzer or wavelength meter from a single interface. It features an automatic lock to RF references, remote locking to optical references and remote locking of TOPTICA cw-lasers to the DFC.

The patented CERO ("zero- f_{CEO}") technology uses difference frequency generation for a passive, all-optical phase-lock of f_{CEO}. This simple and reliable technology offers intrinsic stability and an effective f_{CEO} locking bandwidth as high as the repetition rate of the frequency comb. Advantages of the CERO technology are ultra-low f_{CEO} phase noise and a narrow free running linewidth.

The DFC profits from TOPTICA's 20 years of experience building high-quality scientific and industry-grade lasers. It can be combined with any TOPTICA's world famous cw-lasers and locking electronics to become a complete laser system ready to use from day one after installation.

With its intrinsic stability and ease of use the DFC is the number one choice for anyone looking for high-end performance combined with a high level of robustness.

Applications

- Laser Reference
- High-resolution Spectroscopy
- Optical Clocks
- Microwave Generation
- Dual-comb Spectroscopy
- Direct Frequency Comb Spectroscopy
- Interferometry
- Transportable AMO Systems
- Quantum Computing

Difference Frequency Comb (DFC)

All components overview

01 DFC CORE +
- Frequency comb with CERO technology
- 4 offset-free outputs @ 1560 nm
- All electronics included

02 DFC EXT
- Housing for up to 3 wavelength extensions
- Outputs between 420 - 2200 nm

03 DFC MD
- Monochromatic detector
- Grating-based adjustable filter
- Low-noise photodetector

04 DFC BC
- Beam combiner
- Adjustable split ratio
- Pure cw-light output
- Adjustable power ratio

05 Locking electronics
- FALC - Fast PID controller
- PFD - Phase-Frequency Detector
- DLC EXT housing

06 DLC DL pro

Or any TOPTICA Laser
(420 - 2200 nm)

07 Complete DFC Systems
- Complete stabilized laser systems
- Rack mounted or table top
- Including DFC CORE +, DFC EXT, DFC BC/MD, FALC & PFD, cw-laser, HighFinesse wavelength meter, counter, spectrum analyzer

DFC CORE +
Compact high-performance frequency comb

Class 3B Laser Product EN 60825-1:2007. Visible or insible laser radiation. Avoid direct exposure to beam.
Caution — Class 4 visible or insivisble laser radiation when open. Avoid exposure to the beam.

The DFC CORE + is a robust, 19 inch compatible optical frequency comb. It is the core system for applications like optical clocks, microwave generation or phase-locking of cw-lasers and can be equipped with additional options (page 14) and wavelength extensions (page 10). Its unique f_{CEO}-stabilization is based on Difference Frequency Generation (DFG) and comes with many advantages such as high robustness and ultra-low phase noise. The DFC CORE + features an outstanding stability and accuracy which is suitable for use with the best optical clocks. More than 20 years of engineering experience building high-quality scientific and industry-grade lasers went into its design, it's a TOPTICA laser.

Outstanding specifications

- Comb spacing: 200 MHz
- Stability: $8 \cdot 10^{-18}$ in 1 s*, $5 \cdot 10^{-20}$ in 1000 s*
- Accuracy: $1 \cdot 10^{-18}$ for $\tau > 100$ s*
- Integrated phase noise f_{CEO}: < 65 mrad [70 mHz - 20 MHz]
- Linewidth: < 1 Hz (locked to optical reference)
  20 kHz free running
- Compact dimension: 133 x 450 x 633 mm³, incl. electronics
- Turn-key, full remote control

* Phase-locked to optical reference

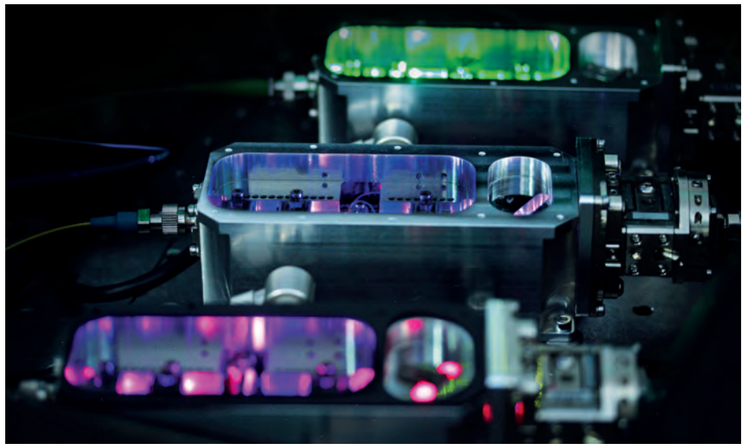
Advantages of f_{CEO}-stabilization by Difference Frequency Generation (DFG)

- Effective f_{CEO}-locking bandwidth = 200 MHz (repetition rate)
- $f_n = nf_{rep}$, perfect for use with optical reference
  Puppe et al., Opt. Lett. **41**, 8 (2016)
- Narrow free running linewidth
- Intrinsically stable
- Simple and reliable
- Passive, all-optical phase-lock

CERO PRINCIPLE: f_{CEO}- stabilization by Difference Frequency Generation (DFG)

CERO: Inherently noise-free
TOPTICA's unique difference frequency comb DFC implements the completely passive CERO ("zero-f_{CEO}") technology, which inherently stabilizes f_{CEO} and the carrier envelope phase.
The DFC is the first commercial system based on this superior patented technology (patent number: DE102004022037). The fiber-based comb combines the convenience and robustness of fiber lasers with low-noise performance.

The CERO principle is described in the following sketch.

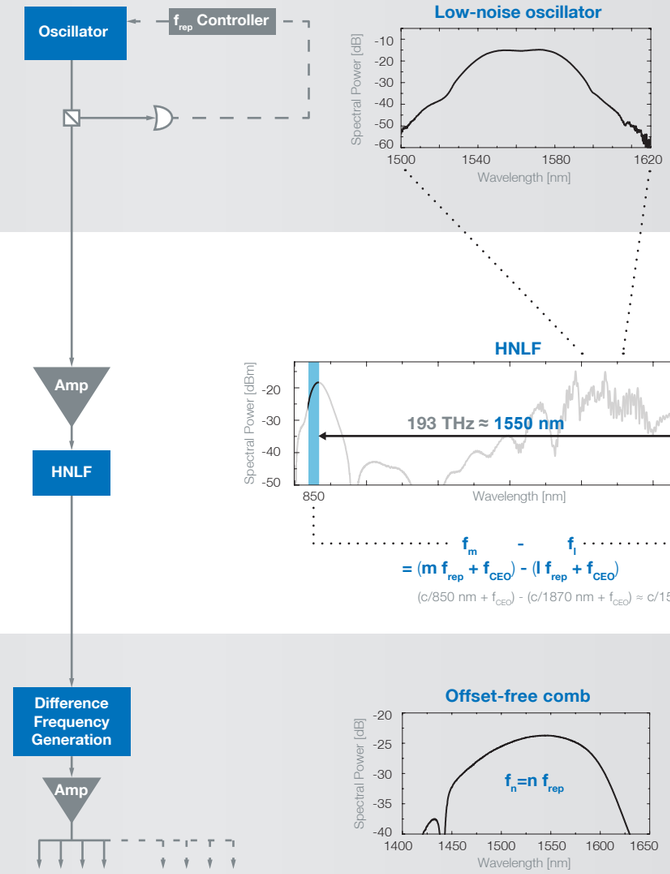


Low-noise Er-fiber oscillator @ 1560 nm

Supercontinuum spanning 193 THz (≙ 1560 nm).

Blue shaded frequencies have identical f_{CEO}.

- DFG between blue shaded frequencies in nonlinear crystal
- Resulting comb @ 1560 nm is: f_{CEO} stabilized, CEP stabilized
- **f_{CEO} is fixed to zero**
- **f_{CEO} and f_{rep} are completely decoupled**
- **New comb equation: $f_n = f_{CEO} + n \cdot f_{rep}$**



DFC CORE +

Compact high-performance frequency comb

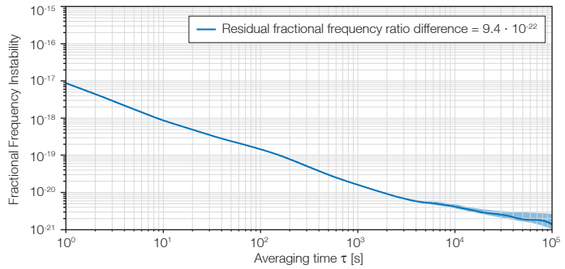
Class 3B Laser Product EN 60825-1:2007. Visible or insible laser radiation. Avoid direct exposure to beam.
Caution — Class 4 visible or insivisble laser radiation when open. Avoid exposure to the beam.

Compact

Fully self-referenced comb including electronics –
Rack-mount ready

Robust

And it stays in lock … !
48 hours in the life of a DFC



High-end

Stability transfer at the 10^{-21} level
Benkler et al., Optics Express [**27**], 36886 (2019)

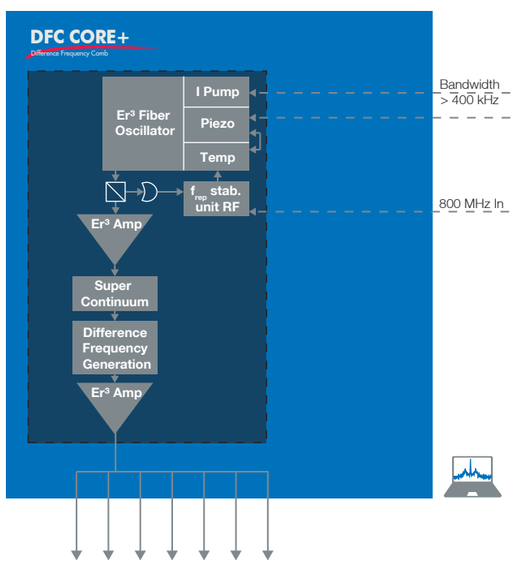
Convenient

Control everything from a single window

Specifications	DFC CORE +	
Center wavelength	1560 nm (other wavelengths see page 10)	
Comb spacing	200 or 80 MHz	
Laser outputs	4 or 8, fiber coupled, polarization maintaining, FC/APC	
Bandwidth	> 20 nm, each output	
Power	> 10 mW, each output	
Integrated phase noise f_{CEO}	< 40 mrad [100 Hz - 2 MHz], < 65 mrad [70 mHz - 20 MHz]	
Linewidth @ 1560 nm	< 1 Hz *	< 30 kHz, typ. 20 kHz (**, free running)
Loop bandwidth f_{rep} lock	> 400 kHz (typ. 450 kHz)*	10 kHz, optimal with DFC RF
Stability	$8 \cdot 10^{-18}$ in 1s *, $5 \cdot 10^{-20}$ in 1000 s*	$1 \cdot 10^{-13}$ in 1 s**
Accuracy	$1 \cdot 10^{-18}$ for $\tau > 100$ s*	$1 \cdot 10^{-14}$ for $\tau > 100$ s **
Bandwidth piezo f_{rep}	> 70 kHz	
Reference	Optical reference*** or DFC RF***, Low-noise oven-controlled quartz (OCXO)	
Reference input	· 800 MHz for RF reference · 10 MHz with DFC RF · High bandwidth I_{mod} (DC - 10 MHz) for optical reference	
Dimensions (H x W x D)	133 x 450 x 633 mm³, incl. electronics	
Cooling requirements	Air cooled	
Power consumption	< 110 W	
Operating temperature	21 ± 4 °C	
Weight	< 30 kg	
Power supply	100...120 V / 220...240 VAC, 50...60 Hz (auto detect)	
Control computer	Laptop, Windows 10, english	

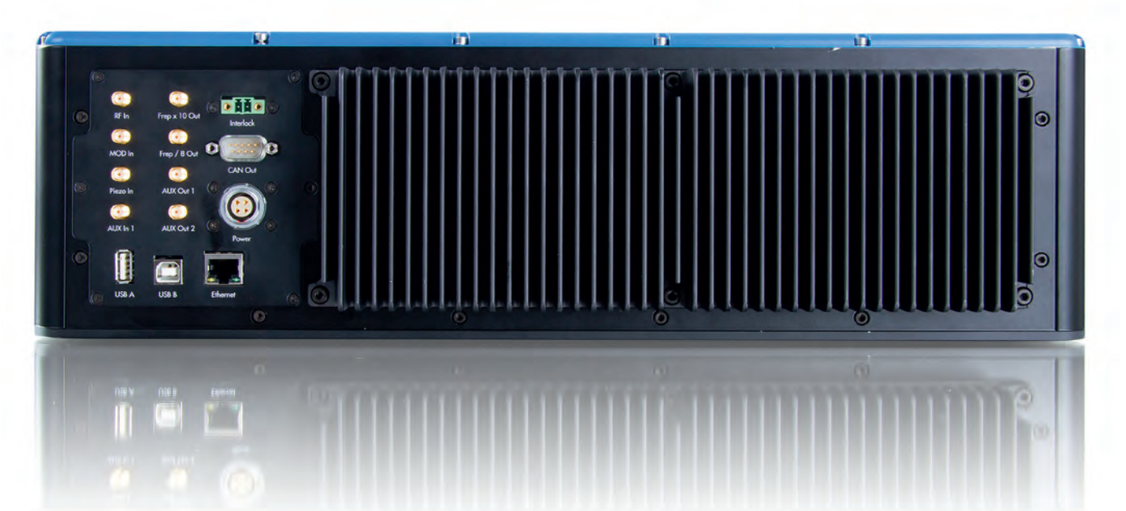
* Phase-locked to optical reference, ** Phase-locked to RF reference, *** not included

DFC CORE +



DFC CORE + includes

- Laser head based on CERO technology
- Robust aluminum housing, 19 inch format, vibration damped optical units
- Driving and RF locking electronics included in 19 inch housing
- Low-noise all PM-fiber oscillator
- Erbium-doped fiber amplifier + HNLF for supercontinuum generation
- DFG unit with CERO technology
- Erbium-doped fiber distribution amplifier
- 4 or optionally 8 offset-free outputs @ 1560 nm



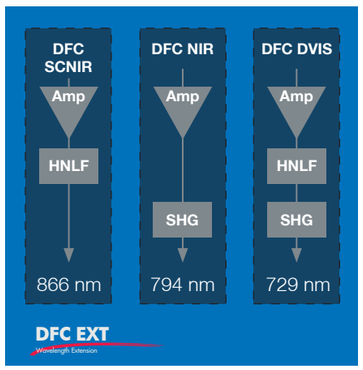
DFC EXT

Wavelength conversion from 1560 nm to 420 - 2200 nm

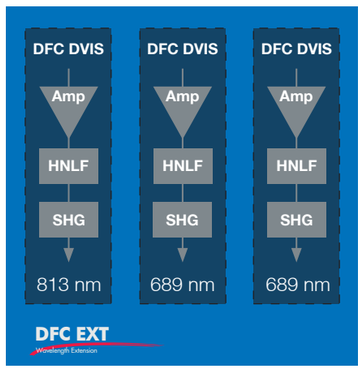
Key Features

- Modular extensions
- For use with DFC CORE +
- Independent remote control of different extensions
- Up to three extensions per DFC EXT
- Custom extensions and beat detection in DFC EXT housing, e.g. single branch dual wavelength

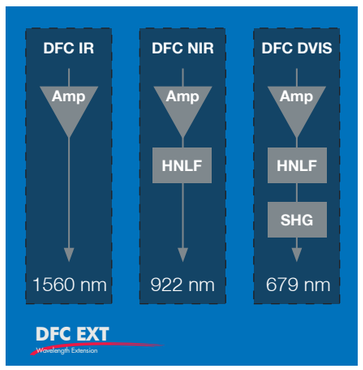
Model	Description
DFC EXT	Housing for Wavelength Extensions
DFC IR	Centered @ 1560 nm, bandwidth > 80 nm, typ. 100 nm
DFC NIR	Centered @ 780 nm, bandwidth > 35 nm, typ. 40 nm
DFC DVIS*	Wavelength range 420 (f_{rep} = 80 MHz), 450 (f_{rep} = 200 MHz) - 860 nm, bandwidth typ. 5 nm @ 698 nm, typ. 1 nm @ 420 nm
DFC SCNIR*	Wavelength range 840 nm (f_{rep} = 80 MHz), 860 nm (f_{rep} = 200 MHz) - 980 nm, bandwidth > 50 nm, typ. 100 nm @ 935 nm
DFC SCIR*	Wavelength range 980 - 2200, bandwidth > 200 nm, typ. 300 nm centered @ 1200 nm
DFC SCVIS	Wavelength range 530 - 900 nm, bandwidth > 370 nm
Other extensions on request, * tunable (patent protected, US 8284808B2), please inquire for more details	



DFC EXT with DFC SNIR, DFC NIR and DFC DVIS



DFC EXT with 3 DFC DVIS



DFC EXT with DFC IR, DFC NIR and DFC DVIS

DFC BC / DFC BCF / DFC MD

Flexible beat detection units

DFC BC

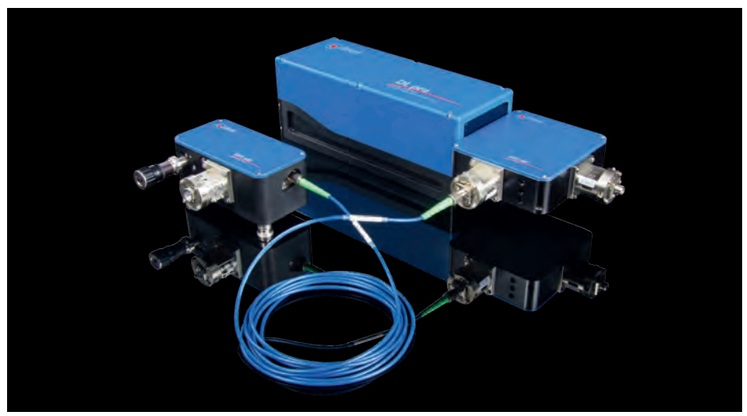
- DFC + cw-laser beam combiner
- Free-space optics, fiber FC/APC fiber coupled
- Available from 420 to 2200 nm
- Adjustable power ratio comb vs. cw
- Comb-free cw output for experiment
- Adjustable split ratio for cw laser
- Wavelength range > 50 nm (depends on central wavelength)
- To be used in combination with DFC MD for beat detection (SM/PM fiber included)
- Dimensions (H x W x D): 49 x 100 x 100 mm³

DFC BCF

- DFC + cw-laser fiber beam combiner
- Available wavelengths 980 nm, 1030 nm, 1300 nm, 1550 nm (other wavelengths on request)
- Fixed power ratio comb vs. cw
- To be used in combination with DFC MD for beat detection
- Dimensions (H x W x D): 23 x 90 x 200 mm³

DFC MD

- Grating based tunable filter, 10 GHz bandwidth, < 1 GHz resolution
- Low-noise photo diode for beat detection
- Available from 420 to 2200 nm
- RF output suitable as direct input for TOPTICA locking electroncis
- Stand-alone narrow band frequency filter
- Wavelength range 50 nm (depends on central wavelength)
- Dimensions (H x W x D): 64 x 60 x 120 mm³

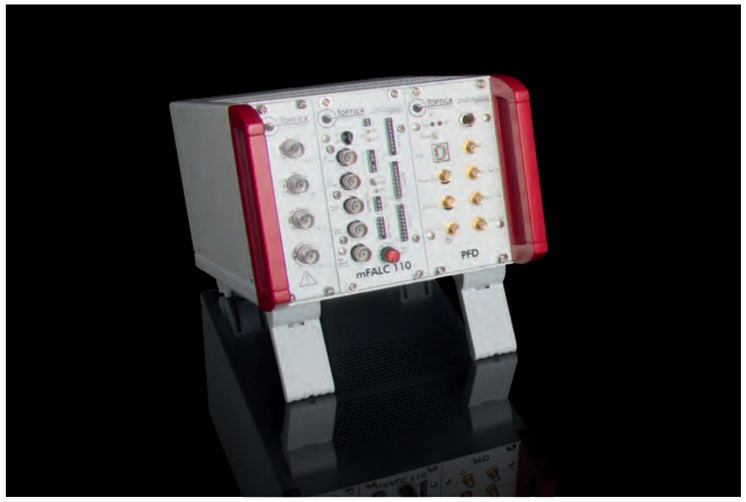


Designed for use with DFC and DL pro.

Locking Electronics: FALC & PFD
Push-button phase-frequency lock

Key Features

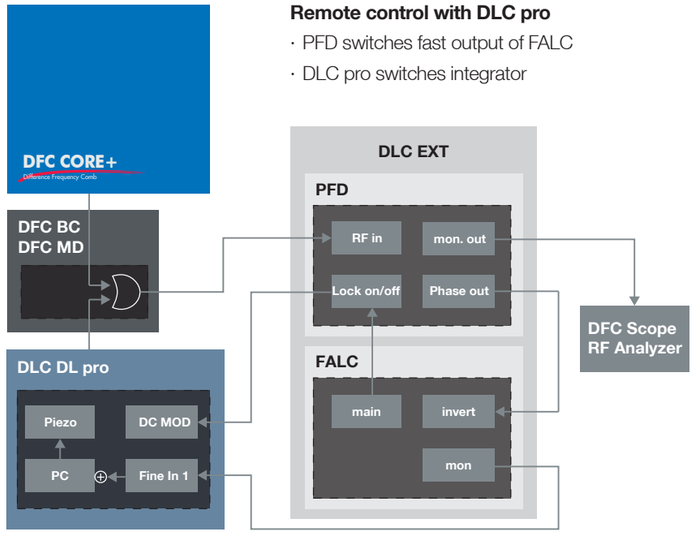
- Robust phase and frequency lock
- Up to 45 MHz bandwidth
- Remote control and locking
- Convenient software interface integrated into DFC GUI (TOPAS DFC)
- Tunable RF source for offset phase-frequency lock
- 10 MHz reference input
- Beat signal conditioning for beat detection and frequency counting



	PFD	FALC110	DLC pro Lock	DFC CORE + internal Lock
Description	Phase Frequency Detector	Fast Analog PID	All-digital PID	All-digital PID
Recommended for lock of DL pro to DFC	✓	✓	✓	
Recommended for lock of DFC to opt. reference	✓	✓		✓
Task	Error signal generation	High bandwidth phase-lock	Slow feedback to DLC pro laser	Slow feedback to DFC
Max. bandwidth		≈ 45 MHz	≈ 30 kHz	≈ 30 kHz
Remote control	✓	via PFD	✓	✓
Rack compatibility	✓	✓	✓	✓
Stand-alone	✓	✓	optional software license for DLC pro	included in any DFC CORE +
Power supply	DLC Ext	DLC Ext		
Dimensions PFD, FALC110, DLC EXT	131 x 184 x 286 mm³			

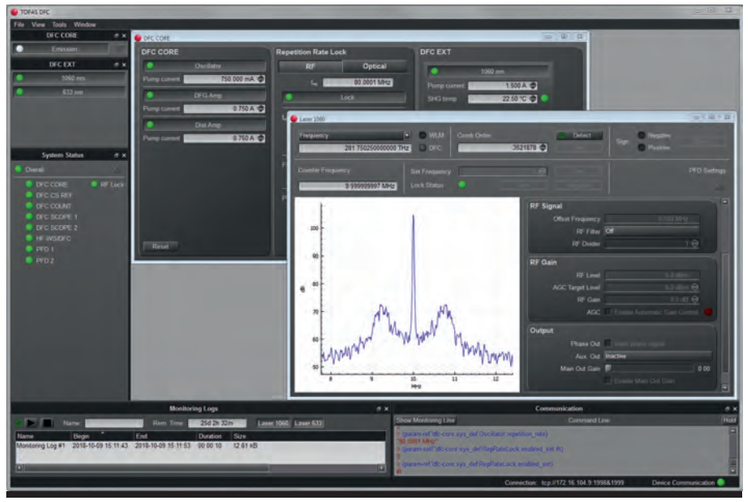
Example: Phase frequency lock of DLC DL pro to DFC

The DFC locking electronics consisting of the Phase Frequency Detector (PFD) and FALC 110 provides high-end phase frequency locking for comb applications. The PFD RF input is designed for use with the RF output signal of the DFC MD. The error signal generated by the PFD is fed to the input of the FALC 110 regulator. The main output of the FALC is passed through the PFD to allow for remote switching of the fast feedback loop which modulates the laser diode current. A copy of the error signal (mon. out) is used to close the slow feedback loop acting on the DL pro piezo (Fine In) with the all-digital PID of the DLC pro.



Remote control with DLC pro
- PFD switches fast output of FALC
- DLC pro switches integrator

TOPAS DFC
Convenient user interface (GUI)



Key Features

- Central GUI for all DFC modules
- One interface for all system configurations
- Remote control
- Remote locking
- Beat monitoring with cw lock status
- Frequency measurement of cw-laser
- Automatic data acquisition and data analysis
- For up to 8 lasers simultaneously

System version	1.0	1.1	2.1	2.2	3.1	3.2	4.1	4.2
System components	DFC CORE +	DFC CORE + FALC & PFD	DFC CORE + FALC & PFD DFC SCOPE DFC COUNT	DFC CORE + FALC & PFD DFC SCOPE DFC COUNT WS8-30	DFC CORE + FALC & PFD DFC SCOPE DFC COUNT	DFC CORE + FALC & PFD DFC SCOPE DFC COUNT WS8-30	DFC CORE + FALC & PFD DFC SCOPE DFC COUNT DLC DL pro FALC & PFD	DFC CORE + FALC & PFD DFC SCOPE DFC COUNT WS8-30 DLC DL pro FALC & PFD
Software function								
Automatic RF lock	✓	✓	✓	✓	✓	✓	✓	✓
Remote optical lock		✓	✓	✓	✓	✓	✓	✓
Lock status		✓	✓	✓	✓	✓	✓	✓
Monitor beat FFT			✓	✓	✓	✓	✓	✓
Count beat frequency			✓	✓	✓	✓	✓	✓
Calculate comb tooth #				✓		✓		✓
Calculate laser frequency			✓*	✓	✓*	✓	✓*	✓
Frequency trace			✓*	✓	✓*	✓	✓*	✓
Automatic data acquisistion			✓	✓	✓	✓	✓	✓
Allan deviation			✓	✓	✓	✓	✓	✓
Remote lock cw-laser							✓	✓

* Comb Tooth # needs to be set manually

One interface for all system configurations

DFC CORE +
@ 1560 nm

DFC CORE +
DFC EXT
420 - 2200 nm

DFC CORE +
DFC EXT
DFC BC /DFC MD

COMPLETE
SYSTEM

Complete DFC Systems
Buy a stable, optical frequency

- All from one single source
- Designed to work together
- Easy to use
- Controlled from a single GUI

Complete stabilized laser systems including the DFC CORE +, any desired wavelength extension, beat units, stabilization electronics, wavelength meters, counters, and lasers are now available from one source.

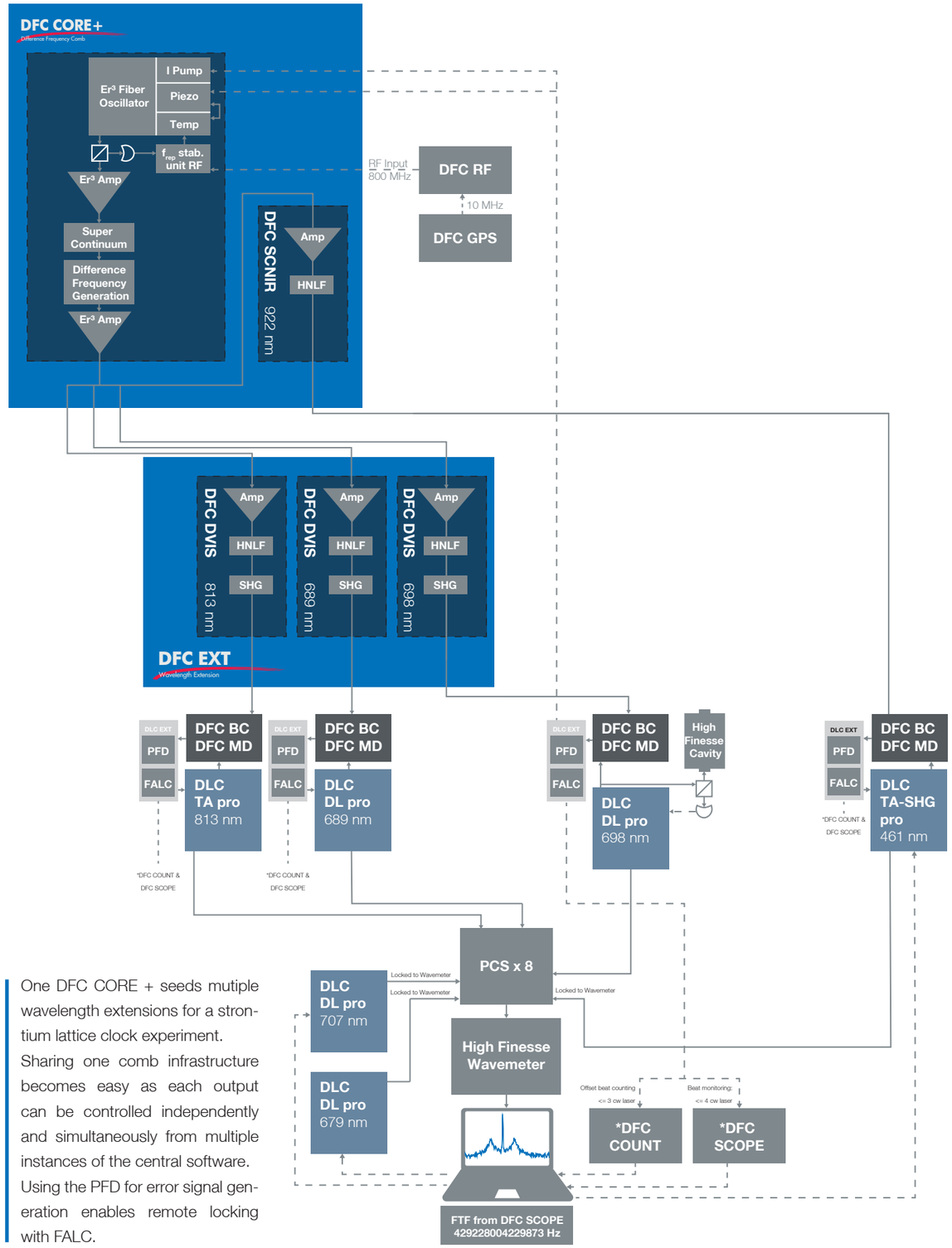
Any of TOPTICA's tunable diode lasers with a wavelength between 420 nm and 2200 nm can be locked to the DFC, lasers

with shorter wavelengths can be stabilized using the fundamental of their SHG unit. The complete laser system is controlled from a single GUI.

	Module	Description
Frequency Comb	DFC CORE +	Difference Frequency Comb, 4 offset-free outputs @ 1560 nm, > 10 mW, > 20 nm
Wavelength extension*	DFC IR	Centered @ 1560 nm, bandwidth > 80 nm, typ. 100 nm
	DFC NIR	Centered @ 780 nm, bandwidth > 35 nm, typ. 40 nm
	DFC DVIS**	Wavelength range 420 (f_{rep} = 80 MHz), 450 (f_{rep} = 200 MHz) - 860 nm, bandwidth typ. 5 nm @ 698 nm, typ. 1 nm @ 420 nm
	DFC SCNIR**	Wavelength range 840 nm (f_{rep} = 80 MHz), 860 nm (f_{rep} = 200 MHz) - 980 nm, bandwidth > 50 nm, typ. 100 nm @ 935 nm
	DFC SCIR**	Wavelength range 980 - 2200, bandwidth > 200 nm, typ. 300 nm centered @ 1200 nm
Reference	DFC RF	Low-noise oven-controlled quartz, output: 800 MHz, input: 10 MHz
	DFC GPS	GPS frequency reference, output: 10 MHz, stability: 1.3 · 10^{-12} @ 1s, 1 · 10^{-13} @ 40000 s
Beat units	DFC BC	Beam combiner for DFC and cw-laser, fiber coupled
	DFC BCF	Fiber beam combiner for DFC and cw-laser, 980 nm, 1030 nm, 1300 nm, 1550 nm
	DFC MD	Monochromatic detector unit, fiber coupled, use with DFC BC / DFC BCF
Locking electronics	FALC	Fast analog 2-channel PID
	PFD	Phase frequency detector, enables remote locking with FALC
	DLC EXT	Housing and power supply for FALC and PFD
Accessories	DFC SCOPE	Digital oscilloscope with spectrum analyzer (FFT), for convenient beat monitoring from software
	DFC COUNT	4 channel counter
	WS8-30	HighFinesse wavelength meter, for convenient determination of comb line number
Rack integration	MDFC	Rack integration of any DFC component and complete comb systems (e.g. MDFC CORE +)

* other extensions on request, ** tunable (patent protected, US 8284808B2), please inquire for more details

Example scheme of complete DFC System
For strontium lattice clock experiment



One DFC CORE + seeds mutiple wavelength extensions for a strontium lattice clock experiment. Sharing one comb infrastructure becomes easy as each output can be controlled independently and simultaneously from multiple instances of the central software. Using the PFD for error signal generation enables remote locking with FALC.

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