Optical Phase Lock Loop (OPLL) with Tunable Frequency Offset for Distributed Optical Sensing Applications

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ABSTRACT

OPLL based on 1550 nm narrow linewidth Planar External Cavity Lasers (PLANEX) with PM output offer several advantages over OPLL based on the conventional DFB or fiber lasers such as bandwidth requirements, high coherent efficiency, absence of the phase reversal and long term locking stability over ambient temperature changes. Such requirements are critical in the field of microwave photonics, LIDAR, coherent optical communications and optical metrology. We report a development of OPLL, optimized for distributed BOTDA/BOTDR Brillouin sensing applications. Conventional approach for distributed fiber optic Brillouin scattering (BOTDR) use a heterodyne architecture for detection of Brillouin scattering signals. With such approach bandwidth (BW) of the optical detector play one of the most critical roles in accuracy of the BOTDR detection. Such coherent detection require a 12 GHz bandwidth of microwave detector which bring excessive noise and high cost of the implementation. OPLL with LO having frequency offset of the order of Brillouin frequency, i.e. 9-12 GHz allow to use low RF BW detection of BOTDR signal. Such detection allow much higher sensitivity, lower noise contribution and offer considerable cost saving for BOTDR distributed sensing and monitoring

Beat frequency stability of OPLL was on the order of few kHz and linewidth of the locked lasers was less then 20 kHz. Coherent efficiency of OPLL was better the 85%. Inherent wavelength stability of ECL (order of magnitude better then any of DFB lasers) allows continuous operation of OPLL without losing locking accuracy. OPLL stability was demonstrated over 48 hours of continuous operation.

Keywords: OPLL, distributed sensing, BOTDA/BOTDR, narrow linewidth ECL

1. INTRODUCTION

Optical phase lock technique is well established approach [1, 2] for fiber optic distributed temperature and strain sensing based on stimulated Brillouin interaction (BOTDA). Such distributed sensing require to have in the sensing fiber contrapropagating pump and probe narrow linewidth lasers with frequency offset close to the local Brillouin frequency to generate acoustic wave with maximum gain. Such frequency depends on local conditions in the sensing fiber and is as linear function of local temperature and strain.

Alternative technique to stimulated Brillouin sensing is a distributed sensing based on spontaneous Brillouin backscattering (BOTDR) when scattering from spontaneous acoustic wave generate Stokes component [3, 4] Such technique does not require contrapropagating pump and probe lasers and relay on the spontaneous generation of Stokes component in fiber. Again, detecting frequency corresponding to the maximum gain of Stokes wave allow continuous distributed monitoring of temperature and strain along the sensing fiber.

"Standard" approach for BOTDR processing based on the coherent heterodyne detection, when a local oscillator is generated from the same laser source. Since Stokes component has Brillouin frequency offset of the order of 9 to 12 GHz such heterodyne detection require the same bandwidth 9-12 GHz. i.e. receiver is operates in microwave range. Such detection generates an excess noise and require an expensive microwave components. Combined with low light level of Stokes signal detection generated by the spontaneous Brillouin scattering such approach unavoidably set a limitation on the detection accuracy, i.e. temperature and strain. Using OPLL with fixed frequency offset on the order of Brillouin frequency allows to frequency offset LO and correspondingly transfer BOTDR signal detection from the microwave to the RF band. In the past, LO with Brillouin frequency offset was implemented using Brillouin laser [5]

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BOTDA architecture :OPLL with Tunable Frequency Offset

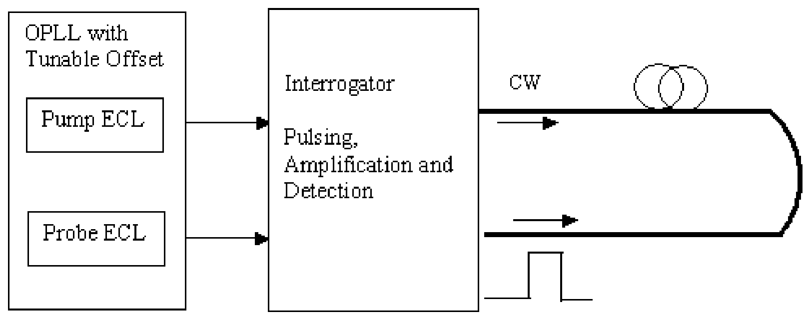

Figure.1

BOTDR architecture: OPLL with Fixed Brillouin Frequency Offset

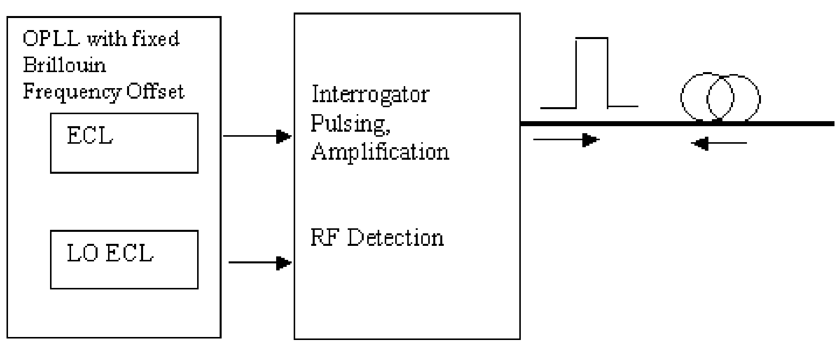

Figure. 2

RIO has developed and packaged low cost optical phase looked loop with tunable frequency offset to address both BOTDA and BOTDR low cost distributed sensing. Such unified approach allow to use "common source" as OPLL with reconfigurable Interrogator. OPLL was developed using proprietary narrow linewidth semiconductor ECL lasers (linewidth less then 10 kHz) build in the standard 14-pin Telecom package

2. OPLL Design and Performance

OPLL was implemented using pre-scaler/4 as an input to a digital PLL. PLL was implemented using DDS with reference oscillator at 60 MHz. Inputs to ECL modulator drive circuitry, PLL and DDS was controlled by μ-controller. OPLL design use short and long term (drift) forward temperature prediction algorithms to assist PLL to acquire and hold lock during offset frequency tuning. The main challenge in OPLL implementations was a loop filter design to compensate on non-uniform FM response of ECL (Fig.4) . Optical block diagram of OPLL is shown on Fig.3

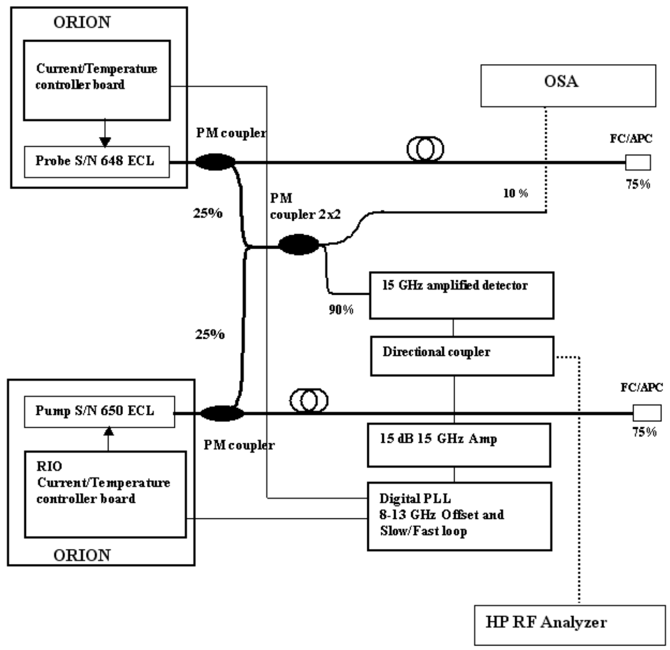

Figure.3

Frequency tuning in ECL is accomplished with a current modulation in the frequency range up to a few hundred kHz In such frequency range dominant mechanism of FM modulation in ECL is a thermal tuning of a FP chip's refractive index by the injection current. DC sensitivity of FM of ECL to the laser current is on the order of 100MHz/mA and to temperature variations 1.8 GHz/C° At high modulation frequencies efficiency of FM modulation is decreasing, Fig.3 show efficiency of ECL frequency modulation in the frequency range up to 1 MHz. At high modulation frequencies (500 kHz -5 MHz) dominant mechanism of FM modulation in ECL is a combination of thermal tuning and adiabatic chirp. Both contribute to the opposite signs (opposite phase) to FM modulation and at some frequency (1-5MHz) there is minimum, so- called phase reversal , Fig.4

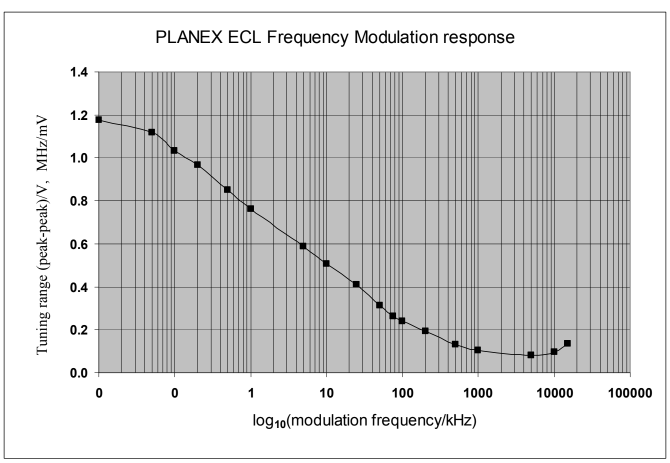

Figure 4

Frequency of the phase reversal is one of the most important parameter in the designing of OPLL. Requirements for BW of OPLL to achieve long term stable locking operation are such that bandwidth of OPLL must satisfy the following criteria

$$\Delta_1 + \Delta_2 < BW < f_{reversal} \quad \text{where } \Delta_{1,2} \text{ are the linewidth of ECL.}$$

Linewidth of each ECL used in OPLL was measured with self-delayed heterodyne technique. FWHM of Lorentzian spectrum were 11 and 12 kHz correspondingly . OPLL loop filter was designed with compensation for non-uniform response behavior shown on the Fig.5 Frequency noise spectrum of ECL was measured with fiber optic Michelson interferometer-Optiphase, Inc , Fig.5

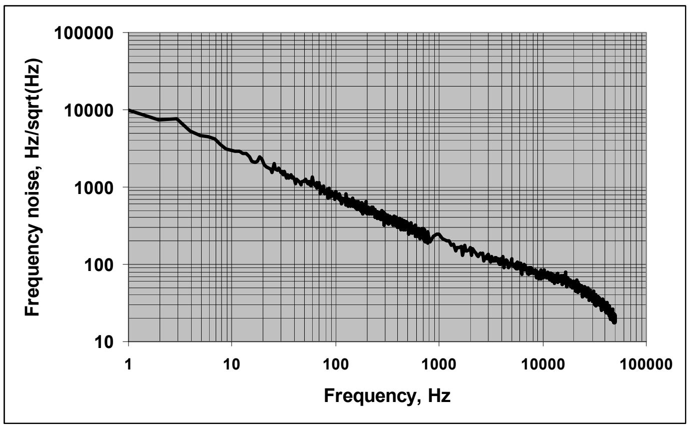

Figure 5

Since sensitivity of FM amplitude to current modulation in ECL is very low (100 MHz/mA-DC, offset frequency tuning in OPLL is accomplished by synchronous tuning of both ECL in the opposite direction, Fig.5

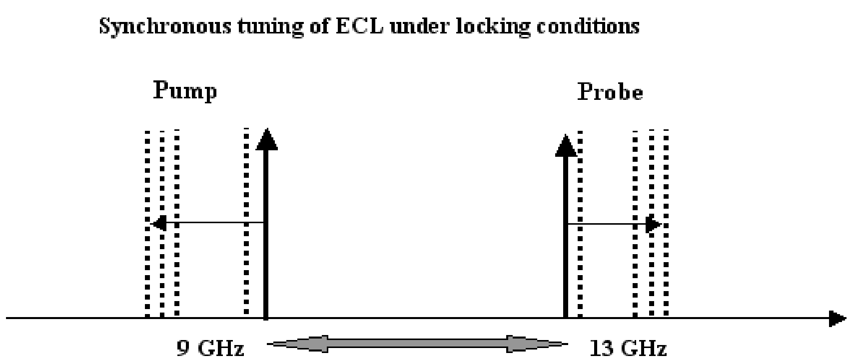

Figure 6

Such synchronous tuning allow achieve wide frequency tuning range 9 t o13 GHz which cover practically all range of existing Brillouin frequencies in different sensing fibers.

3. Table of the OPLL performance parameters

Loop bandwidth	300 kHz	
Probe ECL linewidth under locking conditions	18 kHz	
Pump ECL linewidth under locking conditions	17 kHz	
Locking Frequency Offset	9 -13 GHz	GUI selectable
Tuning steps	100 kHz -10 MHz	GUI selectable
Step tuning speed	.2 - 0.5 msec	depends on step size
Power variation (RMS) over tuning step	0.1% with 5 MHz step	
PSD at 100 kHz offset	70 dBc/Hz	
Optical outputs (PM) per port	5 mW minimum	
Operating temperature	0 to 70 C	
ECL DC FM efficiency	100 MHz/mA	
OPLL continuous locking operation	minimum 48 hours	was demonstrated experimentally

References

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