MEASURING AND REGULATING ELECTROMAGNETIC PHASE IN COMMUNICATION SYSTEMS

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ABSTRACT

Electromagnetic phase measurement is a key measurement technology in optical communication as well as in microwave photonics. The present lecture re-examines recent progress in electromagnetic phase control and its relevance to future communication systems. Electromagnetic phase measurement and regulation techniques are presented while tracing a path through a communication system from transmitter (such as a frequency-stabilised laser) via transmission medium to an electromagnetic detector. An understanding of phase noise at each step in the path and how it may affect frequency standards in optical and rf telecommunication systems is essential.

TRANSMITTER

After briefly recalling fundamental relations between phase and frequency noise, a description starts at the source transmitter, where much work has focussed on the optical noise of semiconductor lasers associated with their extensive application in optical communication, for instance by Agrawal and co-workers [1] – edge-emitting lasers, [2] – VCSEL. The ability to measure and subsequently to regulate optical phase came to the fore when coherent optical communication systems in the late 1980’s were a focus of attention as well as in the development of primary optical clocks [3]. Phase noise in the optical radiation is found for these lasers to be spread over a reasonably large frequency range [4], for instance coincident with relaxation oscillation spectra – see for example figure 1.

Figure 1(a). RIN spectrum (dB/Hz) versus frequency (Hz) of diode laser and shot noise (dashed line) detected at 640 nm wavelength with a 20GHz bandwidth detector [5]
Figure 1(b). Ratio of noise spectrum versus frequency (Hz) of a semiconductor laser, including the relaxation peak at about 1.2 GHz, with and without insertion of a plate optical attenuator

Phase noise occurs at sufficiently high side band frequencies in the microwave range (typically 1 GHz – 10 GHz) as to be relevant in ultra-dense WDM systems, since these frequencies are not an order of magnitude smaller than typical channel spacings. Even more exacting phase control requirements are found in coherent optical communication systems, as well as in the generation of sufficiently pure microwaves from optical heterodyning, where phase noise should typically be less than –100 dBc/Hz at a 10 kHz offset [6, 7]. This kind of performance has been achieved in some schemes, such as combined optical phase locking and optical injection locking (OILPL) [8].
Such dramatic laser line narrowing meets the requirements for photonic generation of microwaves but have not to date been exploited in precision optical frequency metrology. Methods such as these clearly transfer efficiently the spectral purity of a microwave oscillator onto an optical carrier for subsequent transmission, e.g. in a radio-fibre communications link. The absolute optical frequency stability of such OPLL systems is another question.

Corresponding state-of-the-art optical laser linewidths are below 10Hz, such as dye lasers locked to trapped mercury atomic ions [9], at a wavelength of 282 nm, for exceedingly stable optical frequency standards. The use of quantum mechanical squeezing in the quest for ultimate accuracy, where phase noise can be reduced below the fundamental quantum limit in a trade-off against increased amplitude (or intensity) noise, has not been as successful as expected in semiconductor lasers [10], as studied recently in terms of increased phase noise at low frequency with a more comprehensive theory [11].

TRANSMISSION

Varying phase delays when optical signals are carried in media such as fibre need to be controlled not only in high bit-rate communication, but also in transmitting signals for the distribution of time and frequency standards to distant locations. The latter provides, for instance, a ground-based alternative to regular satellite-based time transfer systems, at the nanosecond level [12]. Recent work in 10 Gb/s and 40 Gb/s optical communication in the compensation of chromatic and polarisation dispersion at the picosecond level [13] as well as in local optical fibre links between accurate optical clocks [14-16] promise sub-nanosecond land-based, two-way time transfer over longer distances (> hundreds of km).

In the transmission of electromagnetic signals through a communication system which can include a variety of dispersive optical components, the presence and consequences of optical phase noise need to be thoroughly investigated. Certain system components, such as amplifiers, switches, attenuators etc, can act inadvertently as spectrally selective components, similar to Fabry-Perot or Michelson interferometers, and can be significantly affected in their performance by the presence of optical phase noise and its possible conversion by dispersion to intensity noise. As part of our investigations of new optical wavelength standards in the optical communications C and L bands based on molecular absorption spectra [17, 18] it is quite common to observe spurious interference effects from inadvertent Fabry-Perot effects in for instance molecular cell windows (figure 2).

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RI4 and RI3 lines of CO at pressure 10 mbar

![Absorption spectrum of CO near 1.5 μm wavelength showing cell window interference [18]](image)

Figure 2. Absorption spectrum of CO near 1.5 μm wavelength showing cell window interference [18]
The high sensitivity of present day photonic detection requires that fundamental quantum-mechanical fluctuations in the vacuum state are now commonly included, alongside regular optical fields from light sources, in descriptions of optical signals and transfer functions for various optical systems such as wavelength interferometers [19, 20].

PHOTODETECTOR

In our development of a new method of determining optical photodetector ac response in the microwave photonic range based on shot-noise measurement, we have highlighted the importance of optical phase noise as a prime limitation of the method [5]. A key measurement step in the new method is the insertion of an optical filter. Upon such an insertion, there are possibilities of modifying the homodyne profile by changing coherence relations between light at different frequencies across the laser linewidth, thus limiting the accuracy of the present photodetector response determination method. Figure 1 shows an example of this found in attempting to determine the frequency response of a photo-detector with the present method, where an edge-emitting semiconductor laser at 640 nm wavelength showed prominent a relaxation oscillation peak at about 1.2 GHz. Figure 1(b) shows the ratio of the two measurements of the noise spectrum, including the relaxation peak, with and without insertion of an plate optical attenuator. The ratio is calculated as the square root of the spectral power per unit bandwidth for the two measurements, which should be proportional to the optical attenuation factor, \( A \), of the filter; in the present case equal to about 0.8. It is clear that the optical filter acts as a Fabry-Perot frequency-amplitude converter and reveals that the relaxation oscillation peak has a different coherent frequency distribution from other parts of the measured spectral noise of the semiconductor laser. In this case an attempted separation of quantum shot noise from other noise components failed.

Finally, when the electromagnetic radiation is to be converted at a detector to an electrical signal, questions arise as to the exactness with which optical phase is converted.

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