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Laser Transmitter Adaptive Feedforward Linearization System for Radio over Fiber Applications

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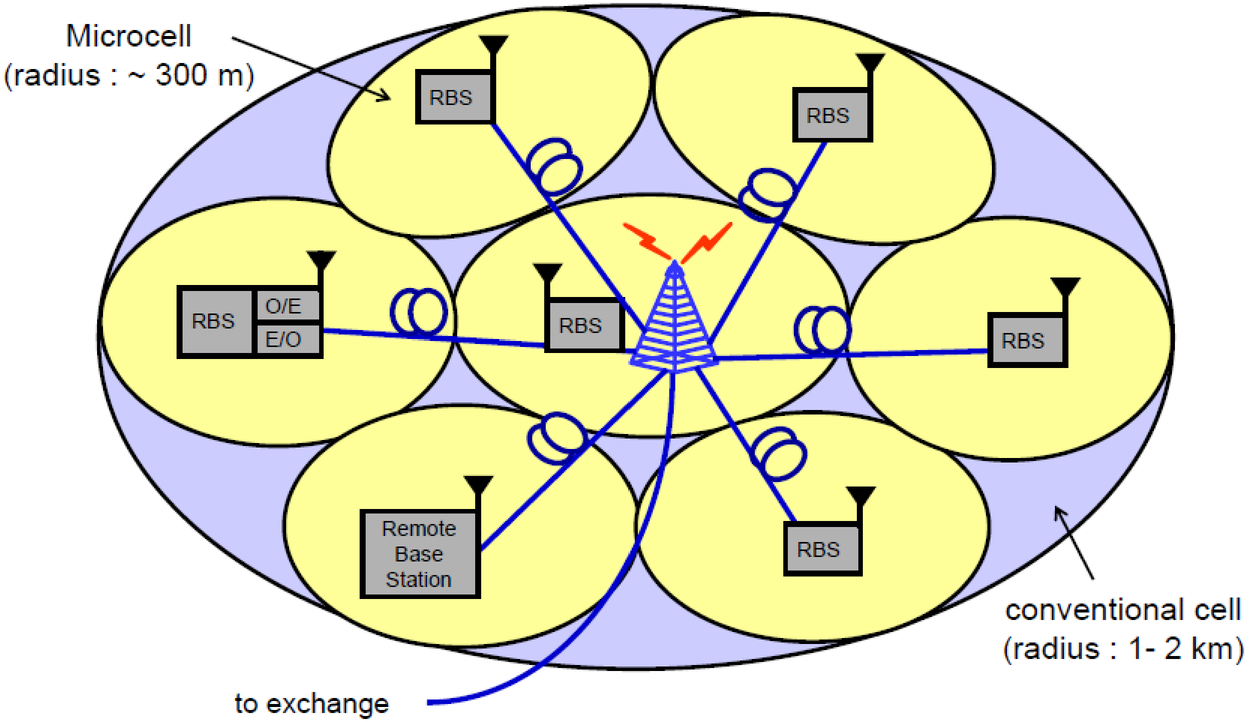
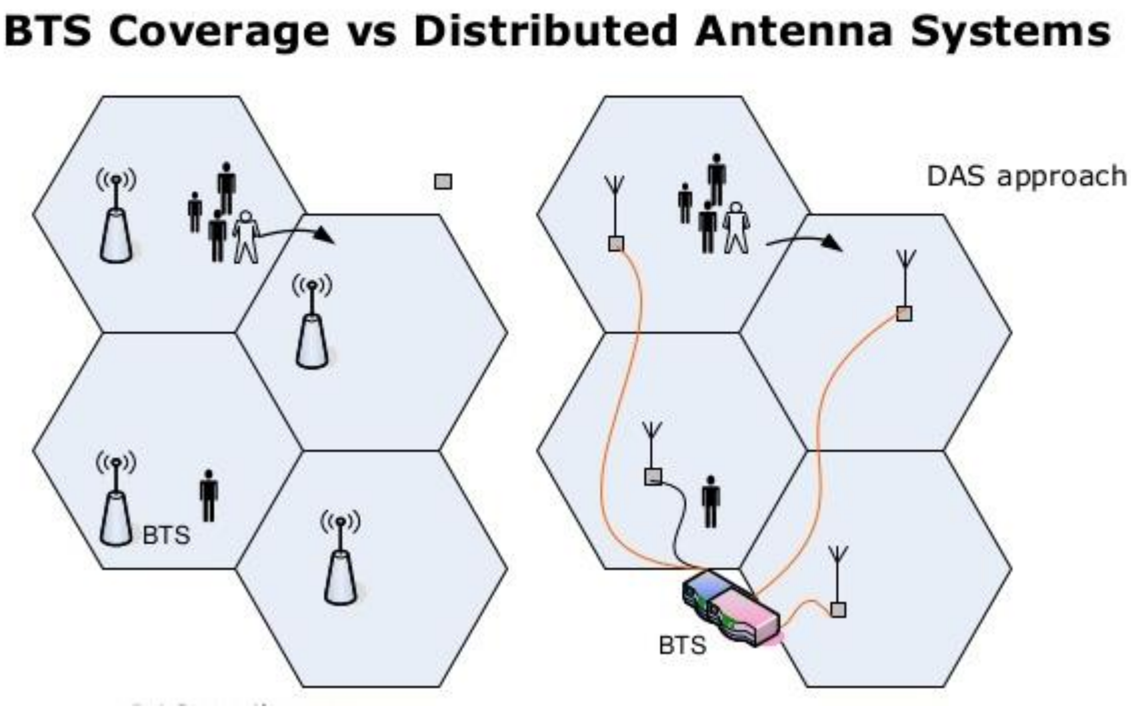
Background

Radio over Fiber Technology:



Smaller cell size:
- Fiber closer to users
- Less user per cell
- Better frequency reusability
- Reduced RF power (EMI)

Background

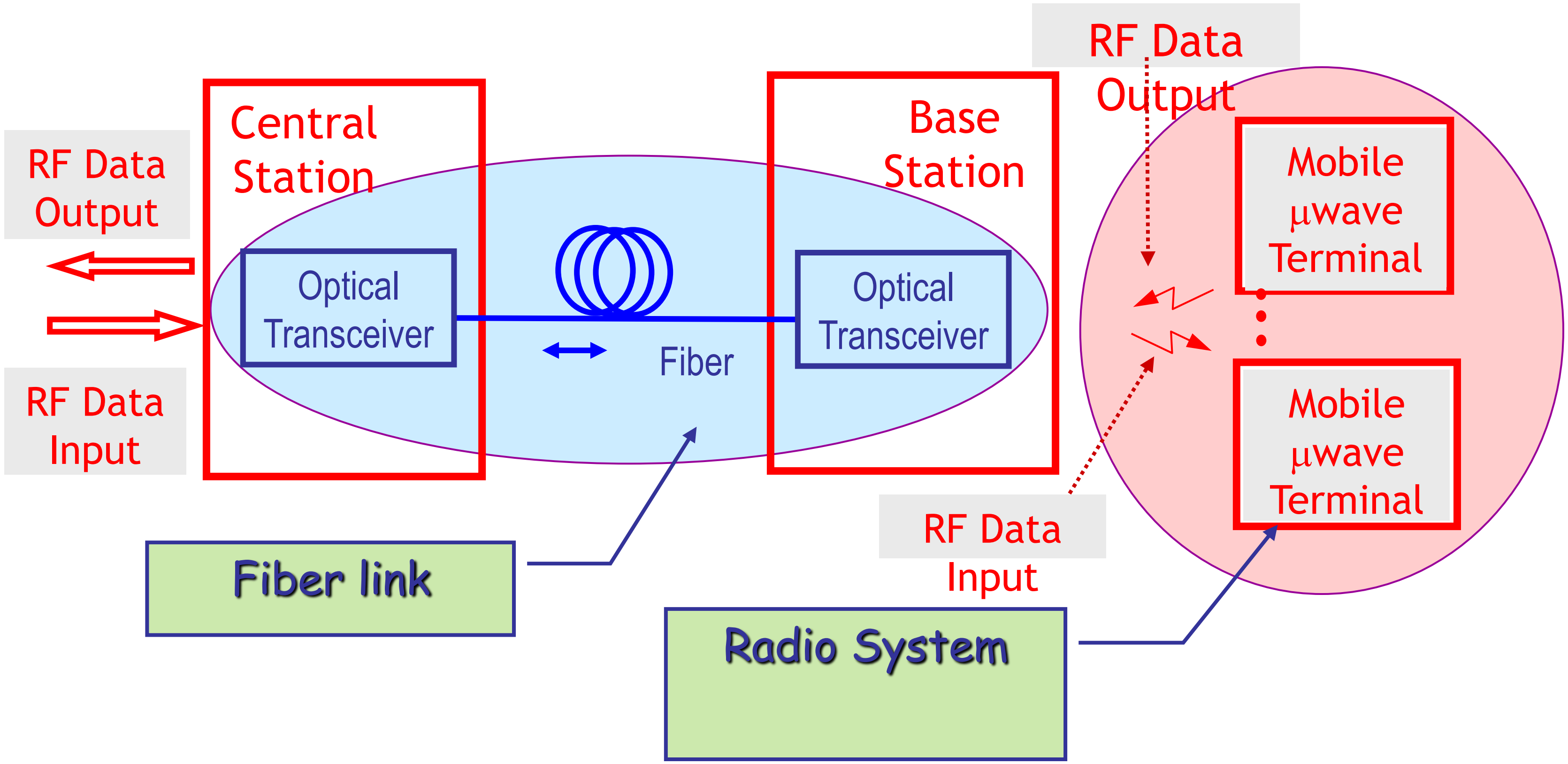


Consolidating signal processing functions:

- Small RAU size and power consumptions
- Easy installations and maintenance
- Perfect coordination between RAUs
- Multi-service operation
- System upgradability and reconfigurability

Background

RoF – Basic Structure of System



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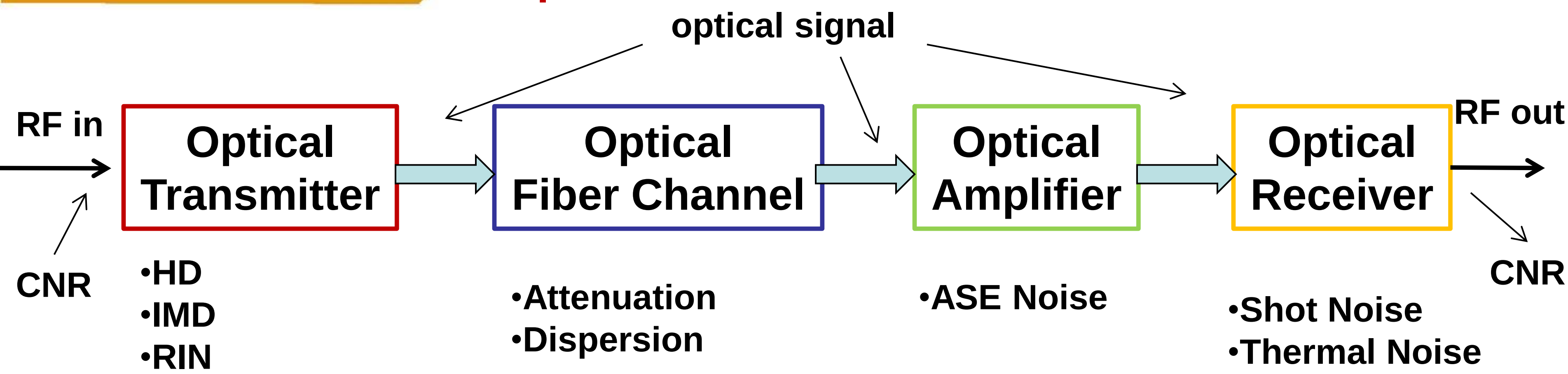
Background

Impairments in RoF Links:



Important link parameters:

- RF gain, Noise figure (S/N ratio)
- linear dynamic range
- bandwidth (bandwidth fiber-length product)

Key issues:

- high-speed, high-efficiency, high-power transmitters and receivers
- devices and fibers nonlinearities
- Low/controlled chirp transmitters (fiber dispersion)

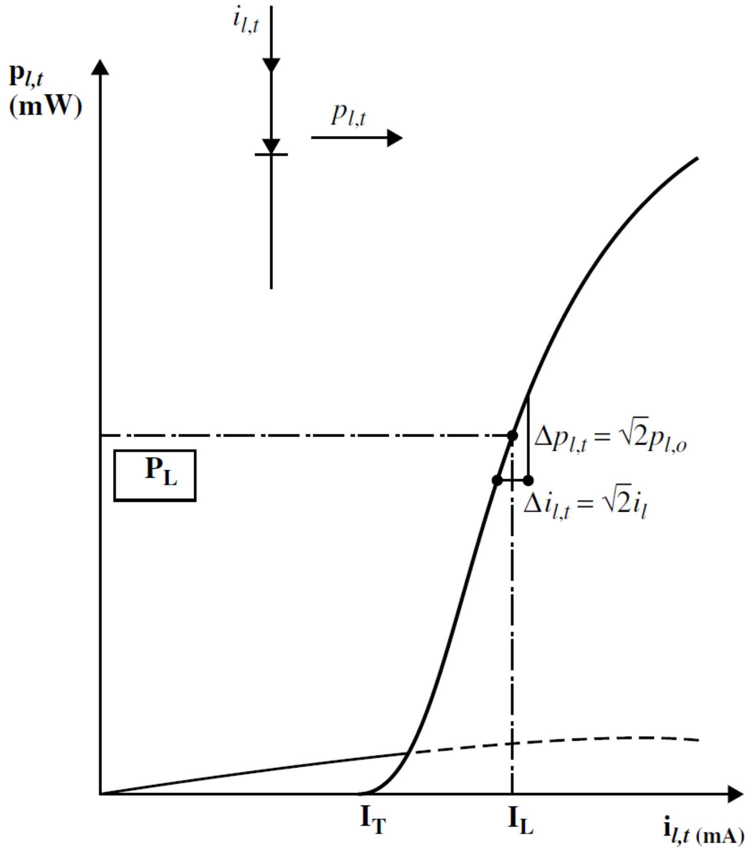
Background

Rate Equation for Laser Diode

$$\frac{dQ}{dt} = \Gamma g(N - N_{tr})(1 - \epsilon Q)Q - \frac{Q}{\tau_p} + \beta\Gamma\frac{N}{\tau_n}$$

$$\frac{dN}{dt} = \frac{I}{eV} - \frac{N}{\tau_n} - \Gamma g(N - N_{tr})(1 - \epsilon Q)Q$$

Dynamic Nonlinear System:
Produce Harmonic Distortion
and Intermodulation Distortion



Background

Linearization Techniques: Quantitative Comparison

Linearization method	Operating frequency	Correction Bandwidth	Correction capability (dB)
Electronic predistortion	Up to 14 GHz	Up to 500 MHz	10 - 25
Feedback	Up to 2.5 GHz	Narrow band	15 - 25
Optical injection	Up to 18 GHz	NA	10 - 25
Dual parallel modulation	Up to 8 GHz	Narrow band	20 - 30
Quasi feedforward	Up to 2.1 GHz	NA	17 - 35
Feedforward	50 MHz–18 GHz	Up to 850 MHz	Up to 38

Background

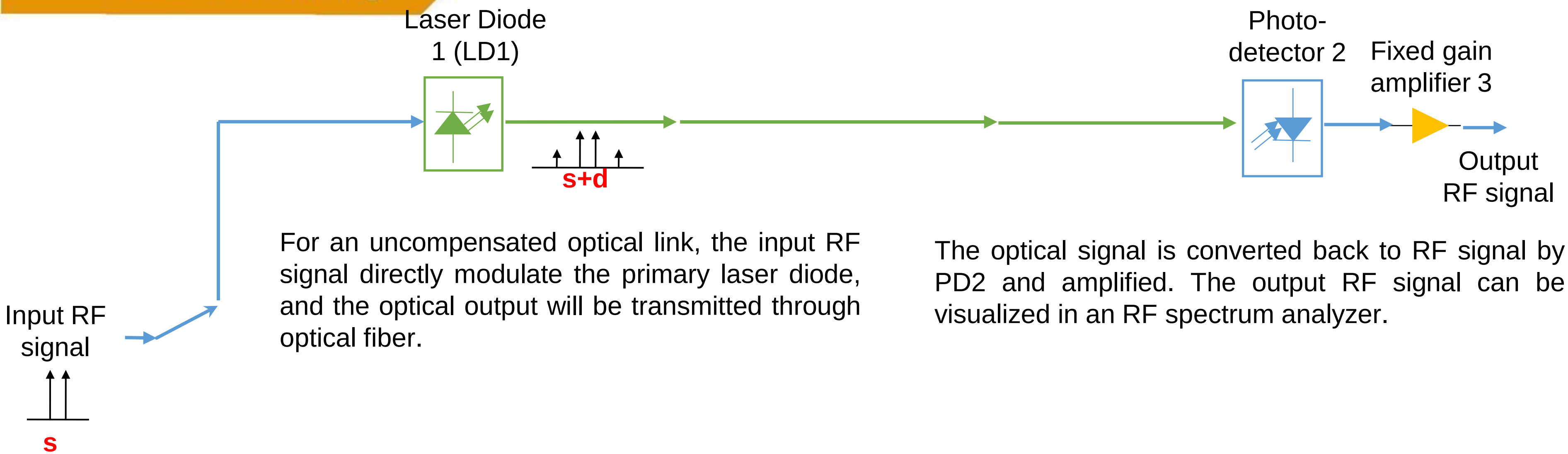
Feedforward: Need for Adaptation

- Feedforward is a sensitive scheme, where the magnitude, phase shift and propagation delay along the feedforward path has to be properly tuned to optimize the distortion cancellation of the system.

- The magnitude and phase adjustments are also bound to be disrupted by any sort of drift and process variations such as temperature effect, laser aging, and input signal variations

- For practical implementations the feedforward system has to be real-time adaptive in terms of its component parameters.

Optical Feedforward



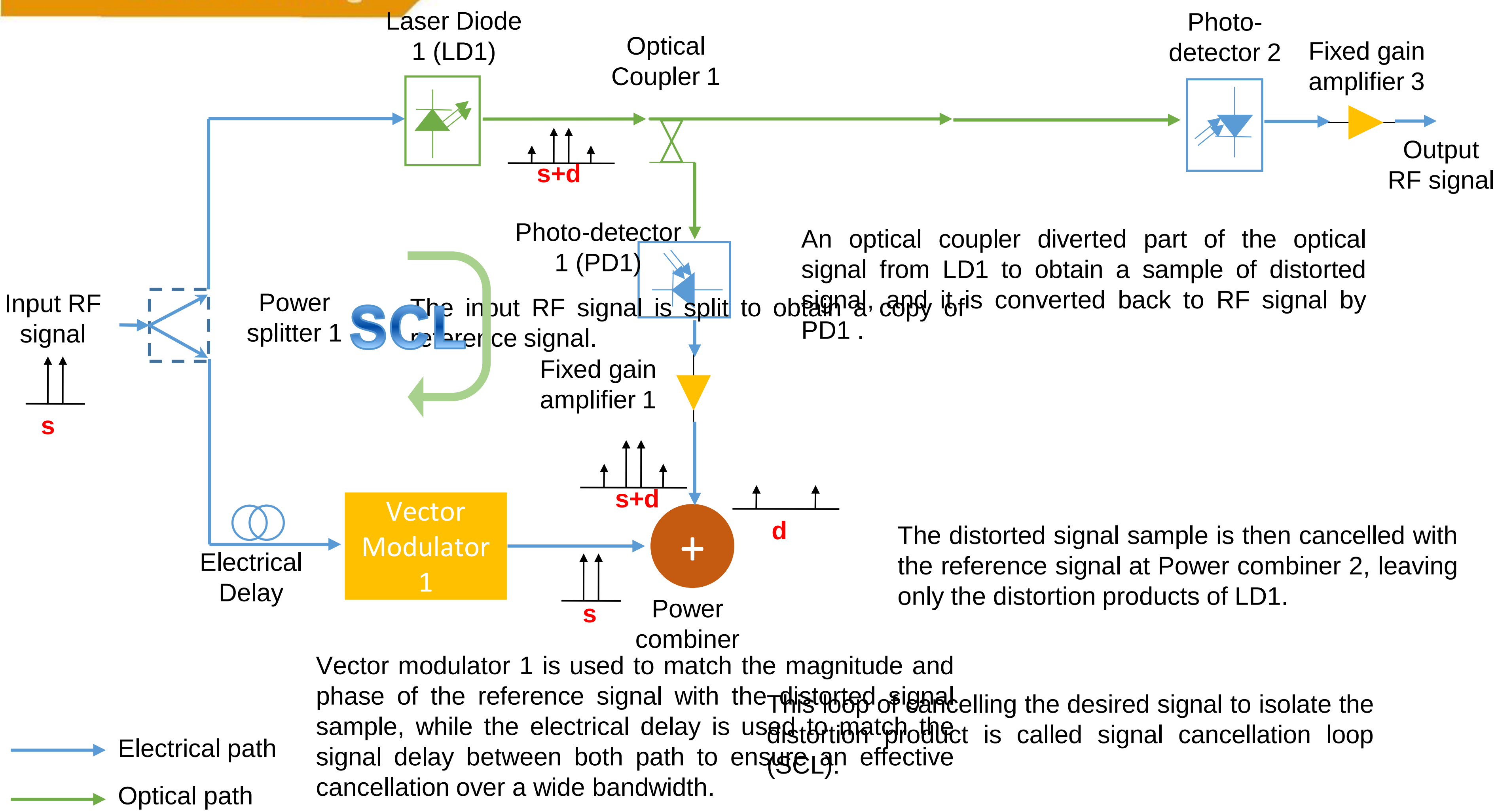
For an uncompensated optical link, the input RF signal directly modulate the primary laser diode, and the optical output will be transmitted through optical fiber.

The optical signal is converted back to RF signal by PD2 and amplified. The output RF signal can be visualized in an RF spectrum analyzer.

Electrical path

Optical path

Optical Feedforward



The input RF signal is split to obtain a copy of reference signal.

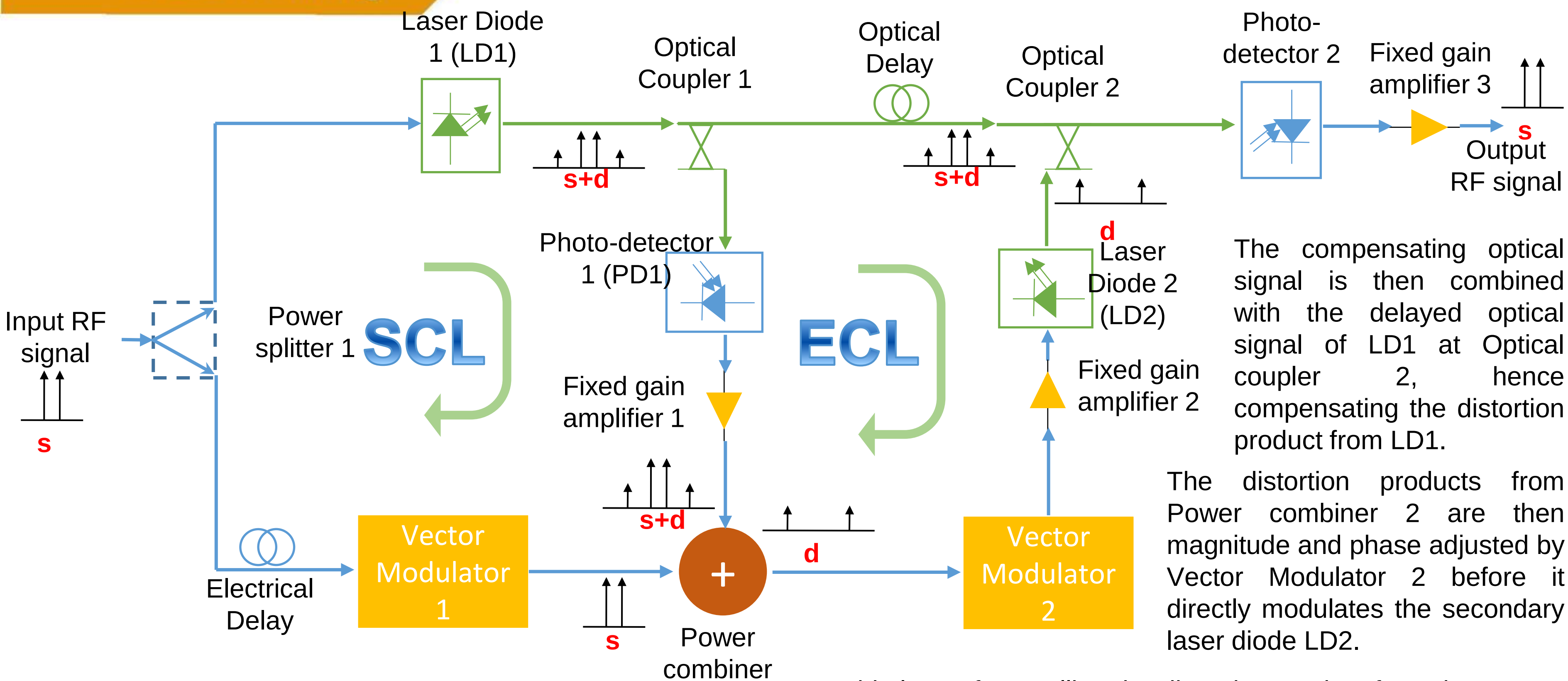
An optical coupler diverted part of the optical signal from LD1 to obtain a sample of distorted signal, and it is converted back to RF signal by PD1 .

The distorted signal sample is then cancelled with the reference signal at Power combiner 2, leaving only the distortion products of LD1.

Vector modulator 1 is used to match the magnitude and phase of the reference signal with the distorted signal sample, while the electrical delay is used to match the signal delay between both path to ensure an effective cancellation over a wide bandwidth.

This loop of cancelling the desired signal to isolate the distortion product is called signal cancellation loop (SCL).

Optical Feedforward



The compensating optical signal is then combined with the delayed optical signal of LD1 at Optical coupler 2, hence compensating the distortion product from LD1.

The distortion products from Power combiner 2 are then magnitude and phase adjusted by Vector Modulator 2 before it directly modulates the secondary laser diode LD2.

This loop of cancelling the distortion product from the primary laser diode output is called error cancellation loop (ECL).

Electrical path

Optical path

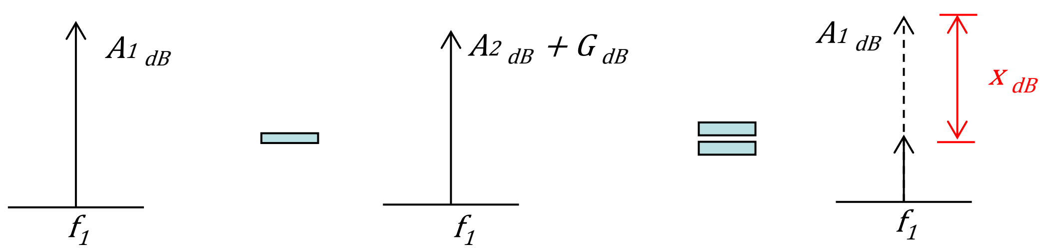
Feedforward Loops Setup

Magnitude and Phase Matching:

i) Adjust the reference signal magnitude close to the original signal
ii) Adjust the reference signal phase till the two signals are in anti-phase

Problem → Nonideality of vector modulator (magnitude adjustment inconsistent over different phase adjustments)

Solution:



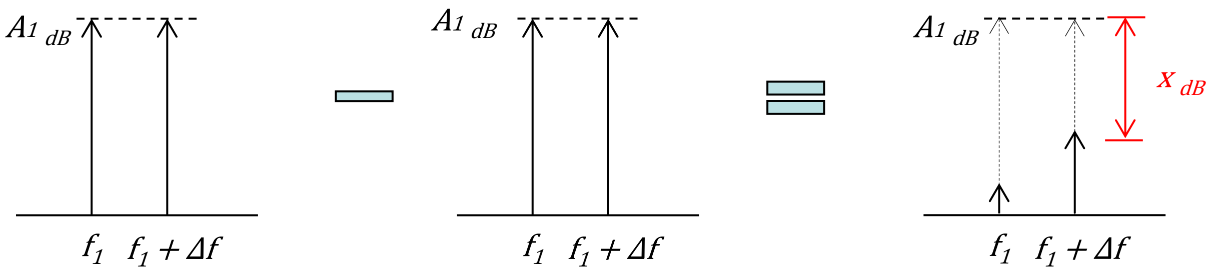
$$G_{i+1\ dB} = G_{i\ dB} \pm 20\log_{10}(1 + 10^{\frac{x_{dB}}{20}})$$

G = vector modulator gain

Feedforward Loops Setup

Propagation Delay Matching:

Cancellation between two identical signals separated by a propagation delay of Δt:



The propagation delay, Δt can be calculated as :

$$\Delta t = \frac{1}{\pi \Delta f} \cdot \sin^{-1}\left(\pm \frac{1}{2} \cdot 10^{\frac{x_{dB}}{20}}\right)$$

The path length difference, ΔL can be calculated as :

$$\Delta L = \Delta t \cdot c$$

, where c is the speed of light constant

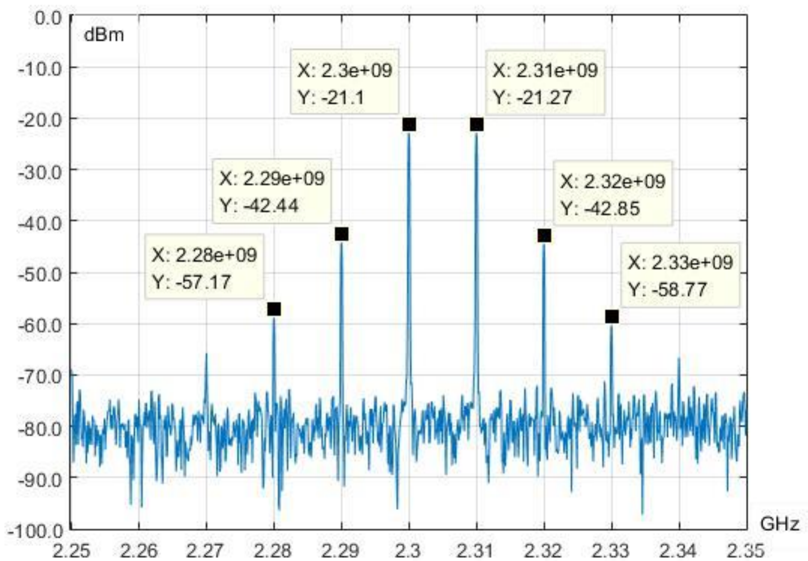
Experimental Results

Device: EA modulator integrated DFB laser diode module

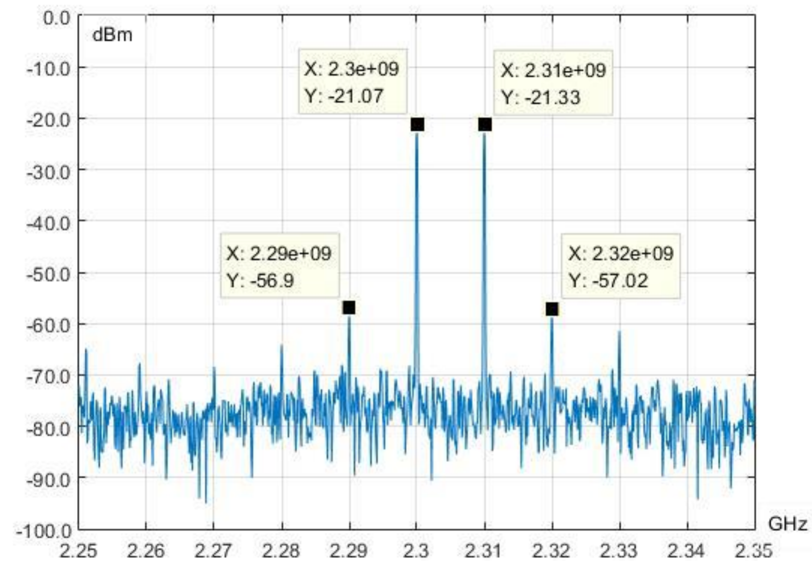
λ_{LD1}= 1547 nm , λ_{LD2}= 1549 nm

Operating Freq: 2.3 GHz

Input power: 10 dBm



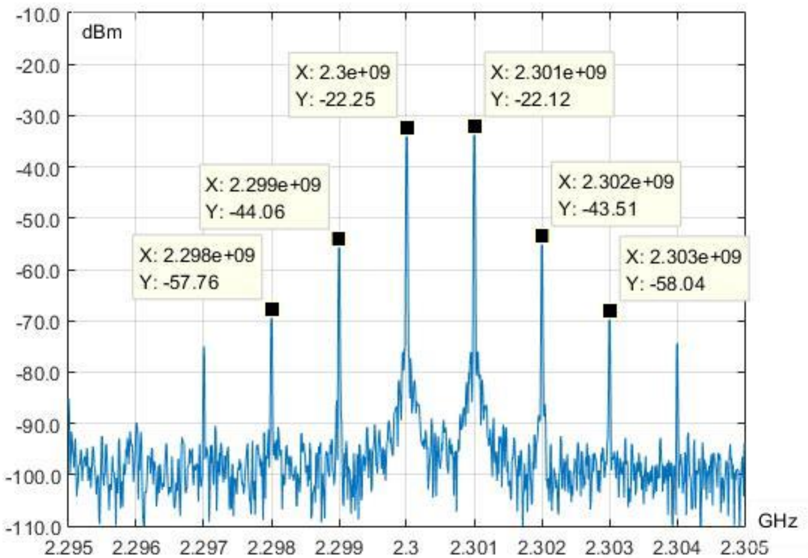
Laser transmitter output before feedforward linearization (10 MHz freq spacing)



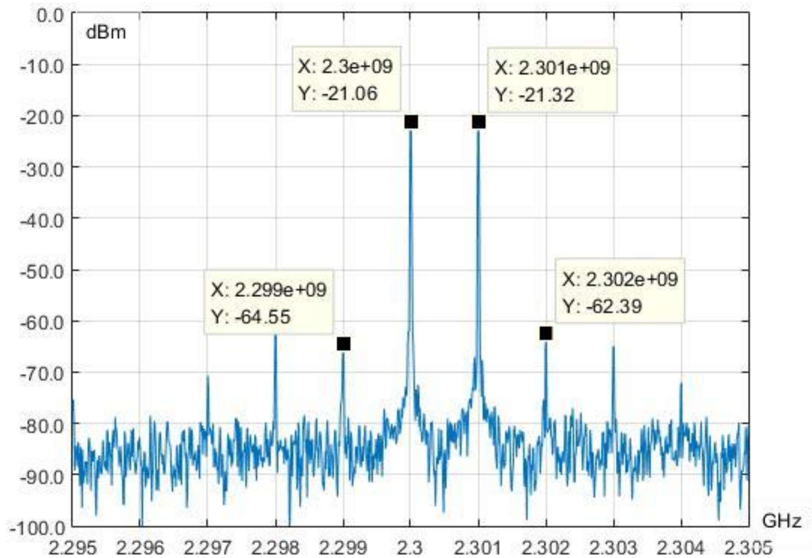
Laser transmitter output after feedforward linearization (10 MHz freq spacing)

The IMD3 level for the uncompensated system is about -21 dBc. A reduction of 14 dB has been achieved for both IMD3 products, equivalent to a bandwidth of 40 MHz.

Experimental Results



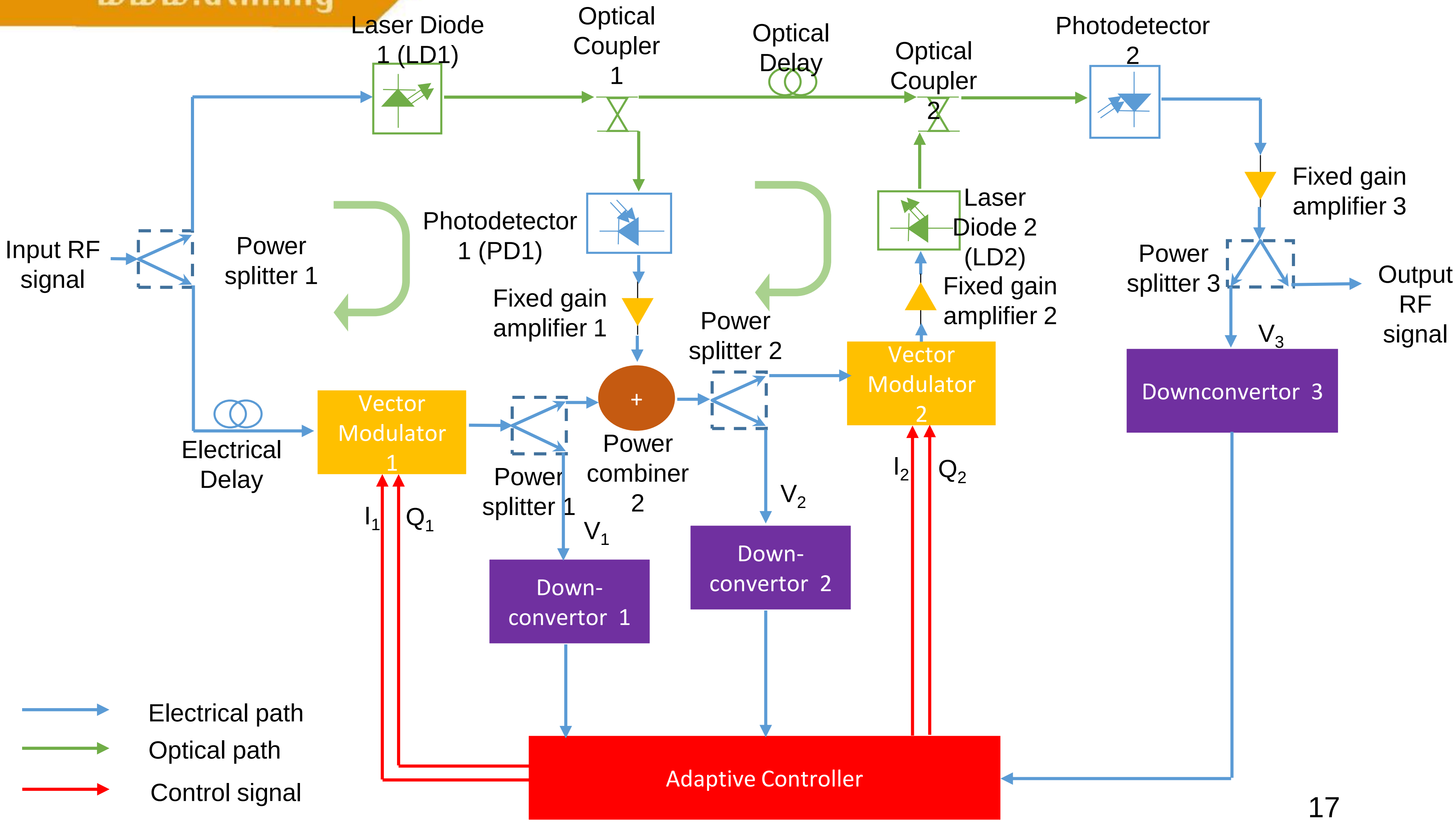
Laser transmitter output before feedforward linearization (1 MHz freq spacing)



Laser transmitter output after feedforward linearization (1 MHz freq spacing)

By narrowing down the freq spacing to 1 MHz, the achievable reduction for both IMD3 products has increased to 20 dB. The system is expected to achieve a larger margin of reduction by further improving the path delay matching.

Adaptive Control System

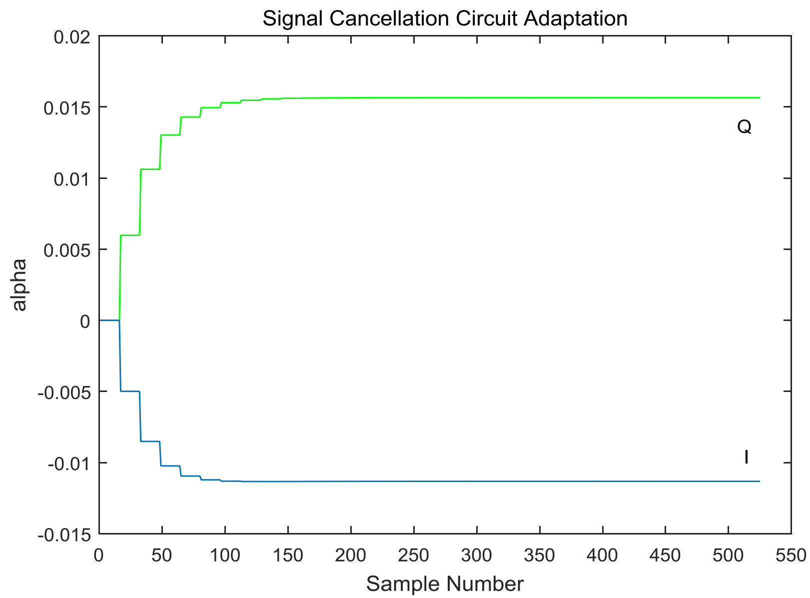


Adaptive Algorithms:

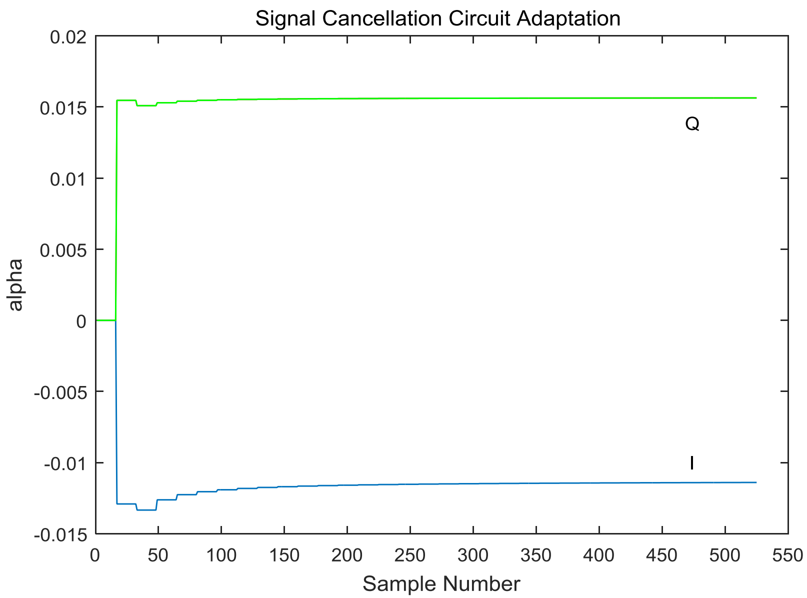
Least Mean Square (LMS) Algorithm:	VS Recursive Least Square (RLS) Algorithm:
$w(n) = w(n-1) + \mu * x(n) * e^{*}(n)$	$g(n) = x(n) / \left\{ \lambda * \Phi(n-1) + \lvert x(n) \rvert^{2} \right\}$ (1) $\Phi(n) = \lambda * \Phi(n-1) + \lvert x(n) \rvert^{2}$ (2) $w(n) = w(n-1) + g(n) * e^{*}(n)$ (3)
Stochastic	Deterministic
Low computational complexity	High computational complexity
Slower convergence	Fast convergence
Mean square error trade-off with convergence speed	Converge to optimal solution
Fast response to input changes	Slow response to input changes

Performance Comparison between LMS and RLS

Signal Cancellation Loop:



LMS

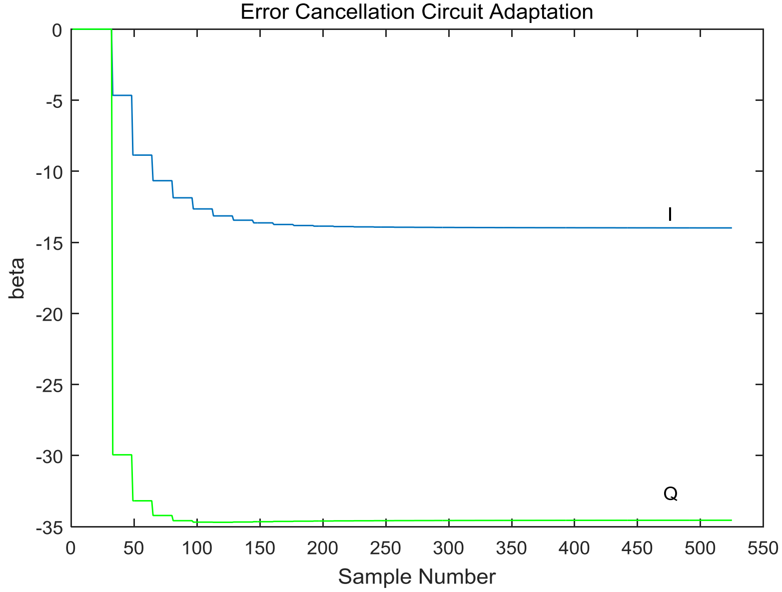


RLS

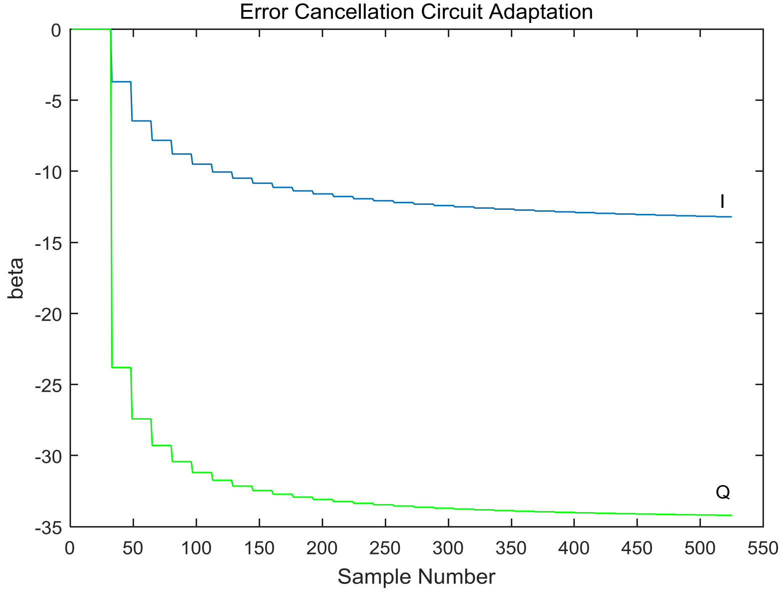
The RLS algorithm is converging faster at the beginning, but the LMS algorithm is settling down more steadily.

Adaptive Control System

Error Cancellation Loop:



LMS



RLS

The error cancellation loop input signal is dependent on the output from SCL, hence it is a time varying signal. It can be seen that the RLS algorithm has poor convergence towards the steady state, while the LMS algorithm is still showing a steady convergence.

Conclusion

- The optical feedforward linearization system has achieved a suppression of 14 dB in IMD3 products over a bandwidth of 40 MHz. Suppression by a larger margin can be achieved with better delay matching.

- On the adaptive control part, the LMS algorithm is chosen over the RLS algorithm in this application because it has shown more stability, robustness, and less computation demanding.

- The outcome of this project serves as the exploration for a future proof alternative for the widely researched predistortion technique, where laser transmitters of even higher performance are in demand for future wireless communication systems in the long run.

Thank You