Optical Signal Processing for Radio-Frequency Arbitrary Waveform Generation and Telecom-Rate Temporal Cloaking

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Ultrafast optics & signal processing using microdevices

Optical communications

Ultrabroadband RF photonics

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Outline

- Photonic RF arbitrary waveform generation
  - application to control of ultrabroadband RF propagation

- Temporal cloaking at telecom rates
  - application of electro-optic frequency combs
Radio-Frequency Arbitrary Waveform Generation (RF-AWG)

Optical pulse shaping & frequency-to-time conversion

Chou, Han, and Jalali, IEEE Photon. Technol. Lett. 15, 581 (2003);
Lin, McKinney, and Weiner, IEEE Microwave & Wireless Components Lett. 15, 226 (2005);
Impulse Excitation of “Frequency-Independent” Antennas

Many antennas are highly dispersive!
(Phase response becomes very important for time domain systems)

Transmitter – Log-Periodic

Receiver – Ridged-Horn

~1 - 2 m

Impulse response

Laser generated excitation pulse

~20 ps

~5.7 ns

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Precompensating Antenna Dispersion via RF-AWG!

Waveforms that self-compress in antenna link

Photonic Arbitrary RF Waveform Generator

Antenna Link

50 GHz Sampling Oscilloscope

Input voltage

Output voltage

Impulse ~195 ps

Chirped: ~2.17 ns

Predistorted

Compressed ~264 ps

Dispersion Precompensation: Spiral Antenna Pair

Input → Spiral Antenna Pair → Received

Long pulse

- BW ~ 1 GHz
- $t_p \sim 1.29$ ns

Short pulse

- BW ~ 10 GHz
- $t_p \sim 182$ ps

Precompensated

- $t_p \sim 470$ ps

Spiral Antenna Pair – Dispersion Precompensation

- Compression achieved for bandwidths up to BW ~6 GHz @ f₀ = 6 GHz (100% fractional bandwidth)

- Limited by pulse shaping time aperture and antenna bandwidth

Strong current interest in space-time focusing through scattering media

Can we use photonics to make ultrabroadband RF waveforms that will self-compress through the scattering channel?

Radio-Frequency Arbitrary Waveform Generation (RF-AWG)

Optical pulse shaping & frequency-to-time conversion

To compensate ultrabroadband multipath RF propagation, we need to make very complex RF waveforms.

We need to talk about limits in frequency-to-time conversion.

see Amir Dezfooliyan and A.M. Weiner, Optics Express (2013)
Far-field intensity proportional to power spectrum of input field

- Requires long enough propagation distance (large enough dispersion)
- Individual spatial (spectral) features stretched to >> their original size (duration)
- For RF-AWG, limits maximum RF bandwidth and time-bandwidth product
A Lens Brings the Far-Field Closer

Space

Lens (spatial quadratic phase)

Output intensity → Angular spectrum

Time domain equivalent:
multiply by quadratic temporal phase
(implemented simply by reprogramming pulse shaper)

- Power spectrum obtained with shorter propagation distance (less dispersion)
- Individual spatial (spectral) features need not exceed their original size (duration)
- For RF-AWG, much larger RF bandwidth and time-bandwidth product
Breakdown of Frequency to Time Mapping (FTM)
(& Complete Compensation via new Near-Field FTM Concept)

Waveform complexity violates far-field condition

- Input spectrum (target waveform)
- Badly distorted temporal waveform
- Distorted RF spectrum

Predicted with quadratic temporal phase

- 41 GHz chirp waveforms
- Input spectrum (predistorted)
- High fidelity temporal waveform
- Ultrabroadband RF spectrum (4 × electronic instruments)

Amir Dezfooliyan and A.M. Weiner, Optics Express (2013)
2-18 GHz Channel Sounding in Multipath Indoor Wireless

Spread spectrum channel sounding waveforms

(mitigating peak power limitations, as in chirped radar)

Retrieved channel responses

Tx: omni-directional antenna; Rx: horn antenna
Non-line of sight @ 10 m separation

Spatially Selective Compensation of the UWB Multipath

- Photonic arbitrary waveform generation over 2-18 GHz bandwidth
  (a factor of two beyond commercial electronic waveform generators)

Tx: omni-directional antenna
Rx: horn antenna;
Non-line of sight
@ 10 m separation

Potential for covert communications & increased data rate

Time Reversal vs. Spectral Phase Compensation

Temporal focusing using electronic waveform generator (0-9.6 GHz)

Omidirectional antennas; through 2 walls, ~14 meter separation

Time reversal (TR)

\[ X_{TR}(f) = H^*(f) \]

Phase compensation (PC)

\[ X_{PC}(f) = \exp(-j \arg(H(f))) \]

Compensated

Channel response

PC shows ~4.5 dB peak-to-average power ratio advantage!

Amir Dezfooliyan and A.M. Weiner, IET Communications (2013)
Cloaking

Bending Light Around an Object to Form a Cloak of Invisibility

Pendry, Smith, Shalaev, …

Proposal for a spacetime cloak?

Actual proposal
Temporal Cloaking

First experiment

Fs amplifier implementation @ ~40 KHz, using four wave mixing w/ specially chirped pulses
What About a Temporal Cloak at Telecom Rates?

Taking advantage of comb generation via electro-optic time lensing

Joseph Lukens

Electro-optic Comb Generation

Phase modulation only
Not very smooth

Flat-topped
38 lines @ 1 dB
61 lines total

With cascaded four wave mixing
75 lines @ 1 dB
>100 lines @ 10 dB

Electro-optic Comb Generation

- Flexible (tunable optical frequency, tunable rep rate, comb generation at multiple wavelengths, …)
- Reversible (only with phase modulators)

Temporal Cloaking at Telecom Rates

Equivalent Spatial Configuration

Phase Grating | Negative Lens Array | Positive Lens Array | Phase Grating
---|---|---|---

Dispersion $\beta_2 L$: $\Phi_T/4$ $-\Phi_T/100$ $\Phi_T/100$ $-\Phi_T/4$

Temporal Cloaking at Telecom Rates

Opening up holes in light at 12.7 GHz

Temporal Diffraction Pattern

Experimental Setup

RF Clock: 12.71 GHz
RF Period: 78.7 ps

Output intensity (Event off)

Cloak on

Cloak off

Power spectrum (midway)

Autocorrelation (midway)

Improving No-Event Operation via Filtering

Filter mitigates unwanted harmonics from periodic cloak

![Graph showing spectral power vs frequency, with labels for cloak spectrum with no event, event spectrum with no cloak, and bandpass filter.](image)
Temporal Cloaking at Telecom Rates

Hiding fast modulations

![Graphs showing periodic event, random data, and specific data with cloaking on and off.

Thank you!

Weiner group 2011-2012