Title

# Light-Generated Morphology



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***Abstract*—Review of coherent combination to create complex geometric shapes. Use of adaptive engineering for interference pattern generation by altering laser pulse timing, phase, polarization, carrier-envelope phase (CEP), and amplitudes of phased arrays to create unique wavevector distribution in space and time, with further analysis of optical detection setup, critique on ambiguities, and quantitative analysis of APD response, SNR, and heterodyne detection.**

## I. Introduction

The combination of the inherit property of light and its wave-particle duality hints at ways light can be engineered. Particles and waves, when looked at separately, exhibit very differing properties. Particles such as electrons can collide, exhibit spin and quantized angular momentums. In comparison, waves have phase and frequency, thus being able to interfere constructively or destructively. Electrons can behave as waves and particles; some behaviors, such as electron diffraction and interference, can only be explained through the wave model. This behavior is expected across physics experiments; when one does not make sense, the other does, an idea addressed by the principle of complementarity [1]. Light exhibits precisely the particle-wave duality, sometimes behaving as a wave or a particle (photon). Both properties in the phased array are used to manipulate the final shape. Particle properties of light, such as spin and orbital angular momenta, play an essential role in this paper's claims and the experiment's ability to produce tightly confined light that retains its shape. In other words, specific conditions allow for focused beams of light to be created and come together to create geometric shapes.

## II. Experimental setup

The setup consists of eight lasers, one acting as a reference laser, which sets the phase lock for the seven beamlines [2]. The LOCSET is for locking optical coherence via single-detector electronics-frequency [3]. This phase control system actively corrects path length differences produced by the emitters and fixes them through feedback. In this case, the LOCSET specifically checks for coherence through the amplitude of the superimposed values consistent with the combination of all the lasers and then modifies each laser to identify which one may be out of phase and fix to maintain coherence across all beamlines. The fix may exceed just one phase; it may be other modifiable boundaries. Figure 1 shows the experimental setup where the stabilized CEP is split to be modified, recombined, and then split for deflection on an APD to analyze light distribution in space and time [2].

## III. Adaptive engineering

As briefly discussed previously, seven of the eight beamlines can be altered after being phase-locked to the reference laser to change the shape of the distribution. The changed parameters are the phase, amplitude, polarization, and timing. The piezoelectric fiber stretcher physically controls the phase the user decides to use [2]. The basis is producing a mechanical, tensile, or compression to modulate the phase using an electric field. It is also likely that the index of refraction changes, so the LOCSET would need to intervene to keep the waves in phase as the wavelength changes. The setup is similar to physical strain piezoelectric effect sensors, which can be used to convert mechanical motion to electrical signals. The paper goes on to argue that phase alone would produce a limited shape; the more varying parameters, the more distributions can be produced; introducing polarization, amplitude, and envelope phase modulation allows for the creation of more complex shapes [2]. Factors that can influence the structure of CEP stabilization are maintained by the LOCSET, amplitude, polarization, timing, and phase [2]. The basis for this comes from the inherent property of light and its degree of freedom, such as amplitude, spin angular momentum, and orbital angular momentum. For example, figure 2, column BC, shows the result of the transverse far-field intensity influenced by the amplitude and phase [2]. Orbital and spin angular momentum also allow the phase to produce various wavefronts and polarization topography [2]. Temporal shifts are essential in changing the phase uniformly across the wavefront. An extra adaptive parameter is channel discretization, which allows for more control over wavefront distribution. An idea like the Fourier series, where more summation of complex sinusoids results in a more ideal shape, but there likely will still be a similar effect in the Fourier series that shows up as the Gibbs effect, so the ideal shape will never be reproduced no matter how much the channels increase. Lastly, timing modification creates differing optical lengths to cause a different interference, thus changing the shape of pulses. This is comparable to phase change, but the modulation with the amplitude is set to 0 or some other value. Additionally, it is related to pulse width modulation, a method used to control brightness on OLED display panels.

## IV. Photodetection setup Critique

The paper does not explicitly mention if the APD is operating in the grain/breakdown or the absorption region; this is additionally tied to no mention of operation by not stating whether it operates in reverse bias or when only when a photon is absorbed is in the breakdown regime. However, because an ADP (avalanche photodiode) is used, it makes sense to assume it is. Nevertheless, more detail is still required to thoroughly verify the grains in noise and performance. The paper also does not explicitly mention the APD material, but for good absorption in the telecommunication range (1550 and 1024), InGaAs, GaAlSb, or InP would be suitable. However, GaAlSb has an advantageous election-hole ionization ratio in the single pass regime, ensuring low noise and allowing for several simplifications in calculations. So does silicon, but semiconductors for silicon are usually used to cut costs; in this case, since there is one, the Ga one is better.

A local oscillator is furthermore used for CEP stabilization, feedback, and general stability. The signal is mixed with the laser phase array, which would condition it as a heterodyne detection due to the acousto-optic frequency shifter producing a beat frequency. However, because it is adaptive, there could also be brief instances of homodyne detection. There would no longer be the need to phase lock the signals vs a homodyne setup. This does not alter any paraments as the output would no longer be a beat frequency pattern; it would only be phase-dependent and produce an easier-to-reach quantum limit as long as phase fluctuations are limited.

## V. Calculations

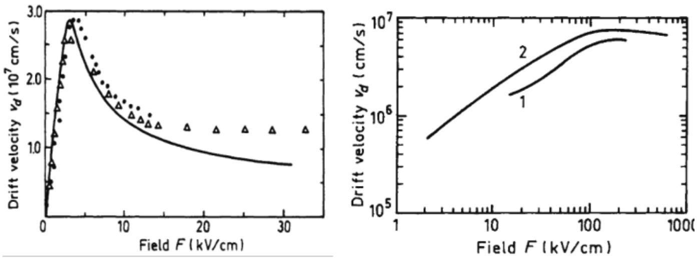


Figure 1: [6] InGaAs drift velocities over a range of electric fields. Left: electrons, right: holes. Useful for ADP bandwidth operation calculation

APD general eq. [4]

M gain: $M = \frac{I}{I_{ph}} = \frac{(\alpha-\beta)e^{(\alpha-\beta)L}}{\alpha-\beta e^{(\alpha-\beta)L}}$ (general eq.)

$\alpha$ = electron ionization coef. /cm

$\beta$ = hole ionization c. /cm

$P = \frac{\alpha}{\beta}$ single pass → $P > M$. only e- contribute to gain

→ High P = Better, less noise

if $\alpha = \beta$

$$M = \frac{(\alpha-\beta)[1+(\alpha-\beta)L]}{\alpha-[\beta(1+(\alpha+\beta)L]} = \frac{1}{1-\beta L} = \frac{1}{1-\alpha L}$$

$\alpha >> \beta$

$$M = \frac{e^{\alpha L}}{1-\frac{\beta}{\alpha}e^{\alpha L}}$$

Figure 2: Gain equations for ADP, additional mention of some properties depending on the ionization coefficient for electrons and holes [4]

Gain variance [4]

$$\frac{\sigma_m^2}{M^2} = 1 + M\left[\frac{\beta}{\alpha-\beta} - \frac{\alpha}{\alpha-\beta}e^{-2(\alpha-\beta)L}\right]$$

$M << P: \frac{\sigma_m}{M^2} = 1$

$$I_{PH}M = \frac{\eta e}{hF}MP = I$$

$$F = 1 + \frac{\sigma_m^2}{M_2} \text{ (excess noise) [4]}$$

$$i^2_{shot}\text{[4]} = 2eI_{Ph}B = 2e(eF)M^2B = 2eI_{Ph}BM^2F$$

$$SNR = \frac{M^2 I_{Ph}^2}{2e(I_{Ph}+I_d)BM^2F + 4KTB/R} = \frac{I_{Ph}}{2eBF}$$

$R >>, I_{Ph} >> I_d$ quant. limited assumption.

Figure 3: Excess noise due to random ionization and SNR with some assumptions for simplification [4]

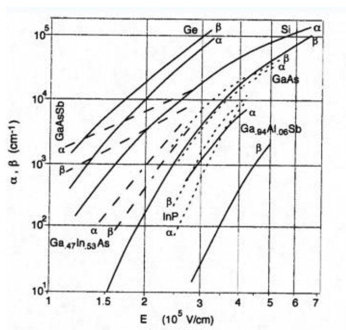


Figure 4: [4] ionization coefficient of electrons and holes per unit length as a function of electric field for a numbers APDs

Assuming GaAlSb APD.

good absorption at 1024nm since within 1.0-1.8um [7] and can op in gain region at correct Bias.

$\alpha = 7 \times 10^2 = 700$

$\beta = 2 \times 10 = 35$

$P = \frac{\alpha}{\beta} = 20$

Since $\alpha >> \beta$

$$M = \frac{e^{\alpha L}}{1-\frac{\beta}{\alpha}e^{\alpha L}} = \frac{e^{(700)(1.5\times10^{-6}m)}}{1-\frac{35}{700}e^{700*(1.5\times10^{-6}m)}} = 1.05$$

$M < P$ $1.05 < 20$ → Single Pass

Max speed and low noise.

$$\tau_t = \frac{L}{2}\left[\frac{1}{v_{e,avg}} + \frac{1}{v_{h,avg}}\right] = \frac{1.5um}{2}\left[\frac{1}{.6\times10^7 m/s} + \frac{1}{.8\times10^7}\right]^{[5]}$$

(at $E \approx 3\times10^5$ V/cm to ensure Imp. ionization)

$= 218.75\times10^{-15}s = 218.8$ fs

$$\tau_{drift} = \tau_t\left(1+\frac{M}{M_0}\right) = 218.75\times10^{-15}\left[1+\frac{1.05}{20}\right] = 230.2 \text{ fs}$$

$$f_{bw} = \frac{M}{2\pi\tau_{drift}} = \frac{1.05}{2\pi(230.2 fs)} = 726.5 \text{ GHz gain Bandwidth}$$

Little change as we're not in multipass regime

Since single pass $\frac{\sigma_m^2}{M^2} = 1$ so $F = 1+1 = 2$

$I_{Ph}$[5] $= I + I_0 + \underbrace{2u\sqrt{I I_0}}_{\text{Beatnote}}$ $\eta = \frac{\text{\# inc. photons abs}}{\text{\# inc on diode}}$

$$I_{LO} = \frac{\eta e}{hf}MP = \frac{M\eta e\lambda}{hc}P = \frac{1.05(.92)\ (1024 nm)\ 140mW}{h(3\times10^8 m/s)} \text{ [7]}$$

$= 80$ mA

Figure 5: Calculations with the use of a GaAlSb photodetector. Several assumptions made, refer to the calculations. [4] [5]

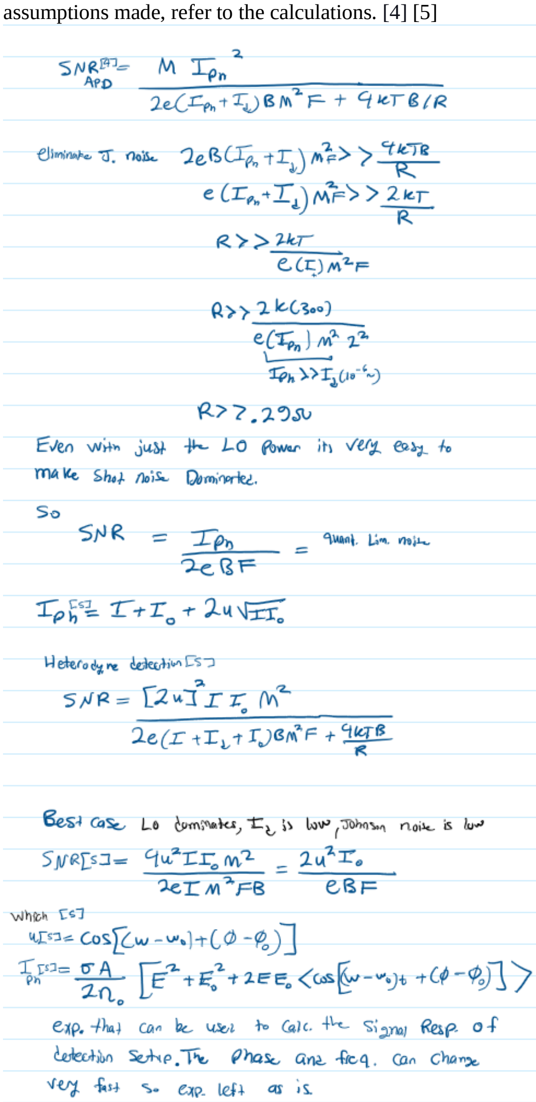


Figure 6: SNR of direct detection of an APD. Estimation on Johnson noise. The required resistor to reach quantum limit without any other design changes. Heterodyne detection SNR and optical power expression. [4] [5]

## VI. Conclusion

Careful modifications of beamline parameters allow light to create specific distributions in space and time. Combining all factors allows for the creation of stable and localized light pulses that construct an interference pattern, which is detected using an avalanche photodiode. Equations that model the output of the APD are outlined with reasonable assumptions additionally outlined and made due to standard design and testing parameters to limit noise.

## References

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