Controlling the Branched Flow of Light through Disordered Media

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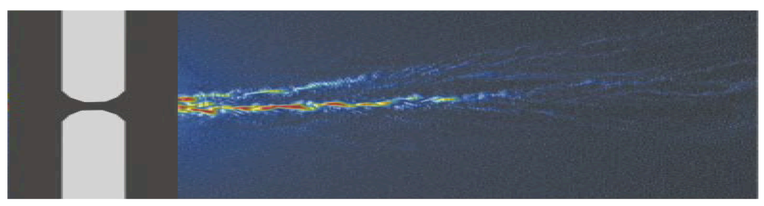
What is Branched Flow?

- first discovered in 2D **electron gas** of semiconductor heterostructures[1]
- **universal phenomenon** occurring for many types of waves[2]
- wave shows **branching behavior** due to the underlying weak and smooth disorder potential



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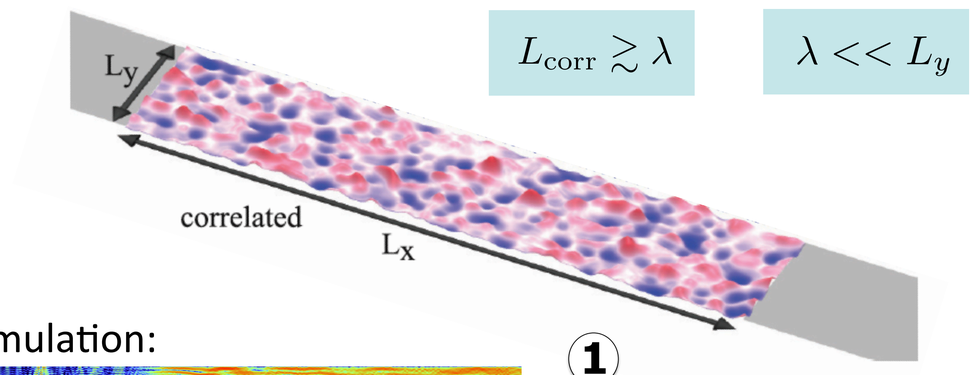
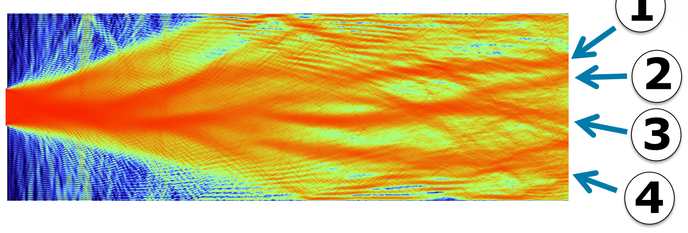
Research Question

- branched flow also possible in **optics**?
- can we control branched flow with **wavefront shaping** techniques?
- prerequisite: weak, long-ranged and disordered refractive index $n(\vec{r})$



$L_{\mathrm{corr}} \gtrsim \lambda$ $\quad$ $\lambda << L_y$

simulation:



wave injected through aperture (left)

goal: transmission of focused light beams **along individual branches**

solution: states with well-defined **time delay** and well-defined **output position** ("particle-like states" [3])

Transmission Matrix and Time Delay

transmission matrix t: matrix elements connect incoming wave in *n*-th channel to outgoing wave in *m*-th channel[4,5]

$$t_{mn} = \left|t_{mn}\right| e^{i\varphi^{t}_{mn}}$$

time delay: **duration** of scattering event **from phase derivative**[6]

$$\tau = \frac{d\varphi^{t}_{mn}}{d\omega}$$

$$q = -it^{-1}\frac{dt}{d\omega}$$

eigenstates of *q* have well-defined **time delay**

effective inversion of transmission matrix using **singular value decomposition**

transmitted flux: proportional to **transmittivity**

$$T = t^{\dagger}t$$

eigenstates of *T* have well-defined **transmittivity**

1st approach: Separation by Time Delay

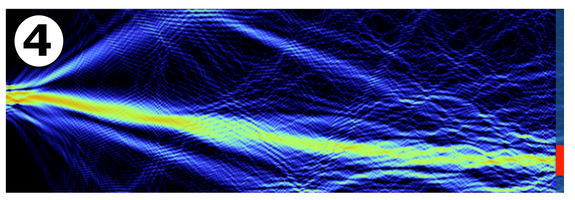
eigenstates of q **injected** from the left

<u>achieved</u>: addressing branches with **similar time delay**

2nd approach: Separation by Branch Position

1) take part of t: input → position of desired branch at output → t_p

2) calculate eigenstates of $T_p = t_p^{\dagger} t_p$



eigenstate of T_p with highest eigenvalue

selected region

<u>achieved</u>: addressing branches with **similar transmittivity** into **selected region**

Solution: Combined Method[7]

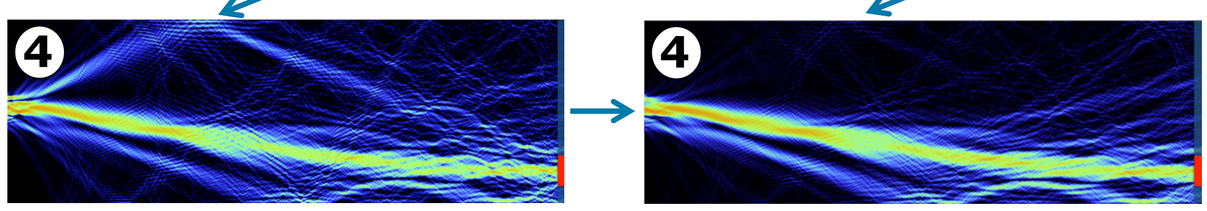
separation by **time delay** + **branch position** → $q_p = -it_p^{-1}\frac{dt_p}{d\omega}$

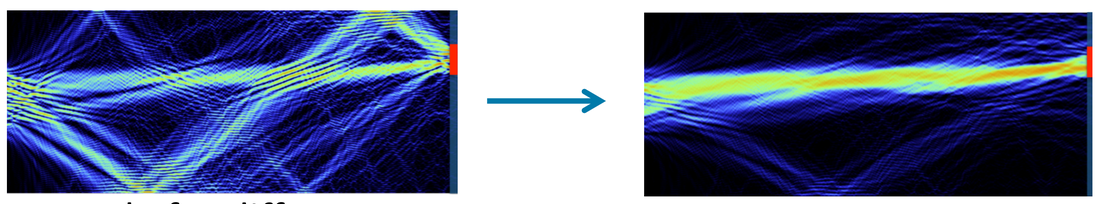
<u>selection by branch position</u>:

contribution with large time delay

<u>selection by branch position + time delay</u>:

contribution vanished





example for different system

achieved: addressing individual branches

Summary

- method to **address individual branches** in branched flow systems
- requires only **t-matrix** → feasible experimental protocol
- procedure applicable to all waves obeying **linear wave equation**

References

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