Wave-Optical Computing Based on White-Light Interferometry

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We introduce a waveoptical computing method based on white-light interferometry. Problems are solved by 1. the modeling of the problem by optical path lengths, 2. the optical superposition of all possible solutions and 3. the selection of the desired solution by interference detection. The method is strongly related to quantum computing but works with purely classical waves.

1 Introduction

We demonstrate the method by the simple example of solving a maze and then give a short overview about a gedankenexperiment for the fast digital-optical computation of arithmetic expressions.

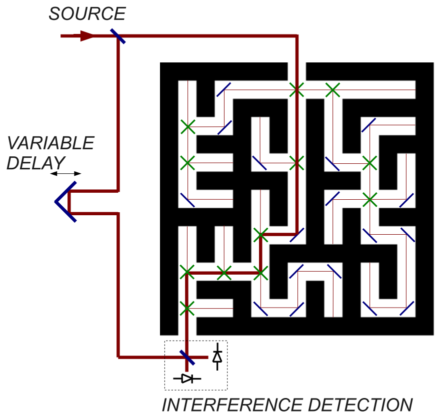

Fig. 1 *Solving a maze by white-light interferometry.*

The basic idea of the method [1] is best demonstrated with a simple problem that already is given in terms of paths. Fig. 1 depicts how we can solve a typical maze problem. The maze is equipped with mirrors so that light entering the maze simultaneously runs through all possible paths. Interference will be detected if the optical path lengths (OPD) of the two interferometer arms are equal. Therefore one increases the delay of the reference arm until interference is detected. Now the input to the interference detector is moved (by an optical fiber) back into the maze to the last junction of the maze. The reference path length will be decreased by the same distance so that we still detect interference. Therefore we can test (by holding the fiber to all possible arms of the junction) from where the "correct" (meaning interfering) light comes. We repeat the process until we reach the input of the maze. For solving the maze we have to make K measurements where K is proportional to the number of junctions along the solution path.

The computational cost of the solution therefore increases proportional to N if we denote the size of the maze by N x N. This should be compared with traditional computer-based algorithms where we have an increase proportional to N^2. This improvement is not obtained for free because the number of photons that are needed for the measurements increases exponentially with N. A detailed analysis shows that for 1 W of power at $\lambda = 1\,\mu m$ and a signal-to-noise ratio of 1 we could in principle solve mazes with about 70 junctions along the solution path. Depending on the type of maze this corresponds to a lateral maze size of some hundred elemental cells. The interference-based detection is helpful since it leads to a better signal-to-noise behavior of the method. In principle it would also be possible to perform the experiment with (short) light pulses. In this case we would detect the time when a pulse arrives at the exit of the maze.

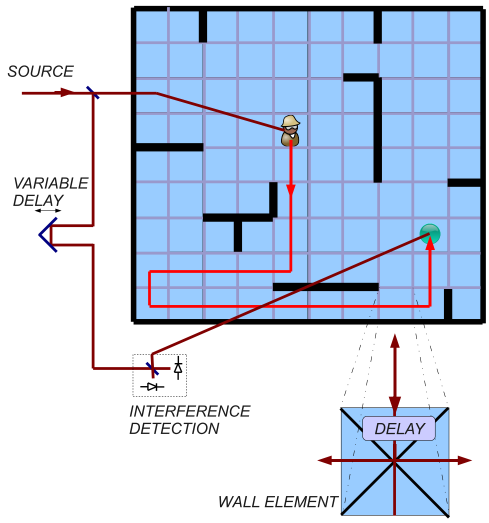

Fig. 2 *Solving the "Ricochet Robot"-Game by white-light interferometry.*

Oltean proposed such a pulse-based method for computing [2]. The main idea is the same as here, namely using superposition of all possible solutions which are coded by optical path lengths. Due to the so-called "coherent gain" that we exploit by interferometric detection we think that interference-based detection is superior for practical implementations but both methods are very similar.

From the computational point of view solving a variation of the maze problem is more interesting. Fig. 2 shows the board game "Ricochet Robots" and its optical solution [3]. This game is NP-complete but still the optical solution can be found by the same method as used for the maze with a small number of measurements proportional to the number of junctions. We just have to replace the walls by "optical wall elements", namely X-cubes.

2 Ultra-fast digital optical arithmetic

Fig. 3 shows a second example of waveoptical computing. Simple arithmetic operations can be performed by appropriate circuits if we code the numbers by optical path lengths. In the example of Fig. 3 of course interference will be detected if C equals A + B. Subtractions and multiplications with fixed constants are equally easy to implement.

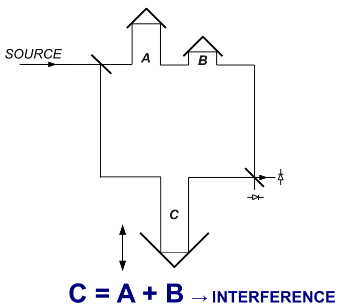

Fig. 3 *Solving C = A + B by white light interferometry.*

For reading (without moving a delay) one bit of the solution in a digital-optical way we might use the setup shown in Fig. 4 which can be easily extend to read all bits of the solution in parallel. Again the main idea here is to use the superposition of all possible solutions by the optical system in the lower path.

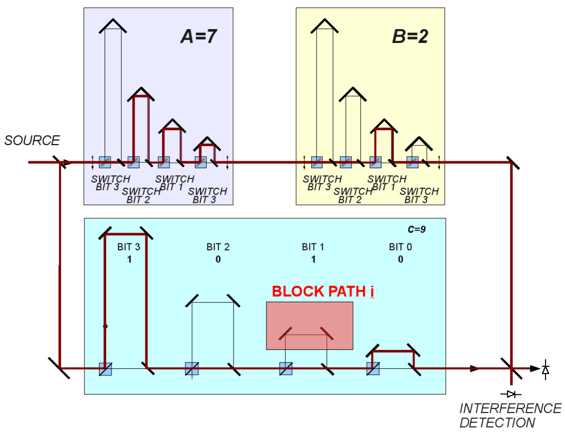

Fig. 4 *Digital optical implementation of addition. Shown is the detection of bit #1 of the solution.*

This optical method is fast only for small accuracy. For a large number of bits the light has to travel through large path lengths resulting in a large latency. Fig. 5 shows a trick for getting completely rid of the latency by using one delay line for every number to be represented. This way the switch that controls the input operands can be located immediately in front of the output (interference detection). Therefore the latency is only given by the time of flight of a photon from the switch to the output. In principle the distance can be made extremely small by integrated optics or photonic crystals.

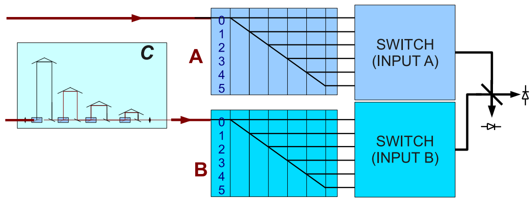

Fig. 5 *Fast digital-optical implementation for subtracting two small numbers (0 .. 5).*

By this method it should be possible to achieve ultra-fast operation in the femtosecond range provided ultra-fast switches and detectors for input and output, but the accuracy would be quite low. If we want to achieve the same high speed when using high accuracy, we have to use residues for representing the numbers because then full parallelization is possible. This will be explained in detail in a future publication.

3 Conclusions

We have shown two gedankenexperiments using the waveoptical computing method. The basic idea of using optical path length, superposition, and interference detection leads to interesting optical solutions of computational problems.

References

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[3] B. Engels and T. Kamphans, "Randolphs robot game is NP-hard!" Electronic Notes in Discrete Mathematics **25**, 49–53 (2006).