Moscow State Technical University named after Bauman

Analysis and development aspects of laser optical disk systems

Khrouchtchev Serguei
Moscow State Technical University named after Bauman
Moscow, Russia

Paper submitted to ETRIA World Conference "TRIZ Future 2003" held at Aachen, Germany, on November 12-14, 2003.

Summary

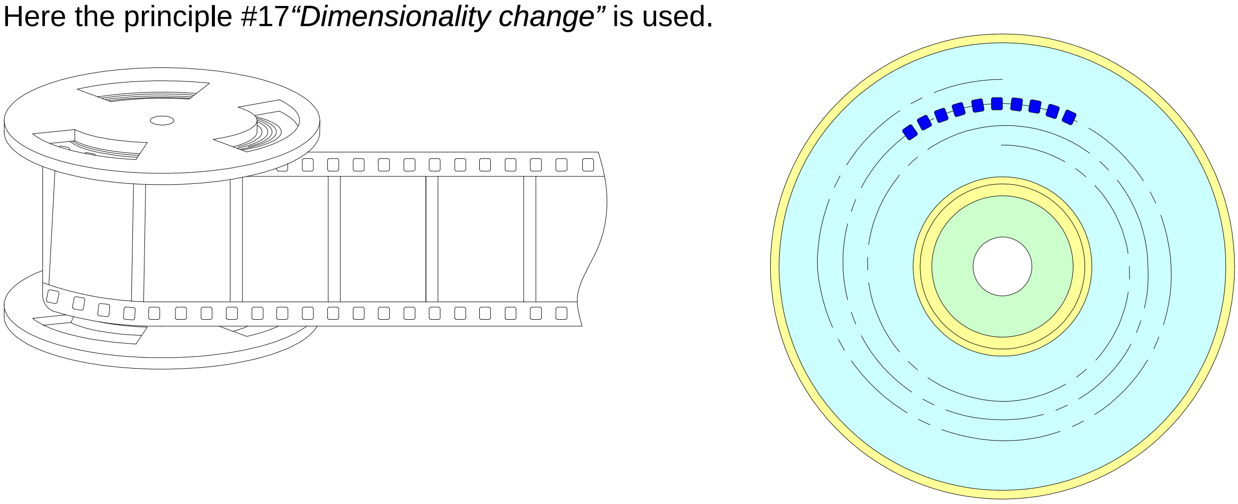
For a new qualitative and rival product designing it is necessary to make prediction of technical system development. Patent analysis is an inseparable part of the prediction project. Methodology of prediction designing that is used in this article consists of the following stages:
1) patents database composition which is covered of studied area;
2) search for a key solutions which are determined currently using systems and elements (by using of patent database); changing tendentious of technical system's users performances;
3) search for unrealized in mass-production solutions;
4) system analysis of all device elements (to fetch out useful and harmful functions of all system elements in concrete device);
5) prediction trees for each system elements and system at whole are designed by using of prepared above materials.

As an example analysis and development aspects of optical disk systems is presented. Here are given tendentious of the future optical disks systems development; presented system analysis of currently used devices; shown methods of prediction trees designing.

This article is well coordinated with the Codes of technical systems development and could be used as education guidance for the TRIZ teaching.

Systems of optical recording are used since the end of 19 century when first photography was made. Further development is allowed to increase density of analog recording (for example, holography) and speed of recording (high speed recording in physics) but ability of such recording is highly limited. And first of all there are limited by chemical development process. This was the major point when people were started to think about digitizing of optical recording.

By 1970 all archives of movies studios and even movie-cameras users were full by film cassettes. Moreover films on the nitrocellulose base are fire riskiness. It was showed by a lot of fires. By then specialists of Philips had suggested and tested idea to solve all the problems: to copy and store information not at the films but at a relatively thin glass disks. This was realization of the idea to store spiral track of microframes like spiral film in cassette (**Fig. 1**). Here the principle #17*“Dimensionality change”* is used.



Cine-movie cassette

Movie disk

Figure 1

System was designed, disk written. Problems had appeared during first operation. Fuzzy image was noised by so-called “snow”. This significantly showed that there were a lot of problems in system. These problems were a result of two major reasons: disk shape and disk mounting at a spindle of the motor (**Fig. 2**). In principle, these problems are easily removable by system adjustment. But when disk is changed we will get problems again until system will be readjusted. And the other problem is that one disk could contain much smaller frames than one film’s cassette.

So problem was divided onto two:
1) it is necessary to follow continuously to frames track;
2) it is necessary to increase disk capacity.

To make continuous tracking for disk surface (focusing) and spiral track (tracking) is enough easy. It is

Eccentric disk

Wobble disk

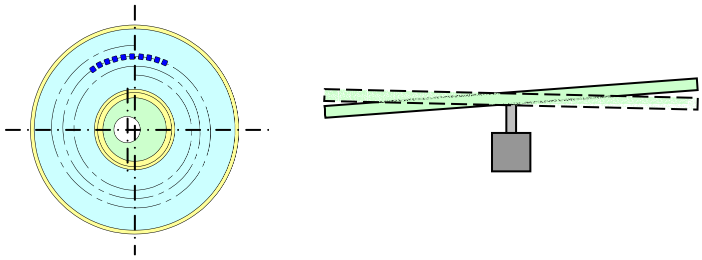


Figure 2

necessary to use two control systems with stabilized feedback (principle #23 *“Feedback”*) to get good results (tracking system evolution is also very interesting question which will be highlighted in next publications). But increasing of disk capacity is not such easiest task. Frames became smaller and smaller until they reach physical limit of optical system. After this virtual threshold optical system could not correctly reproduce image. And even in this case quantity of frames could not be compared with even one film cassette. How to increase information storage capacity? This question became number one.

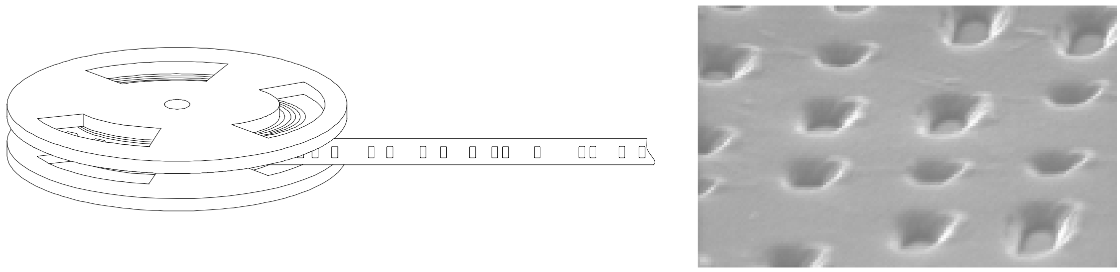
At that time engineers of Philips had already widely used computers. These were giant devices in a half of room. And one of these engineers could see possible solution in computer input device!

- How do we input information into computer?

- By means of perforated tape.

- Right, this is just paper tape with holes! Computer reads this holes and decodes information that stored there. And in analogy with the perforated tape we also can code information into sequence of holes!

So the result of this possible conversation was laser optical recording system that (in analogy with perforated tape) is burned out holes in metal foil (**Fig. 3**).



Perforated tape’s cassette   Disk surface

Figure 3

So here the principle #1 *“Segmentation”* is used. Image was coded at a number of tiny holes in metal foil layer and finally information density increases in thousands times and at one 30 cm disk was recorded few film cassettes. At those time holes became such small that it was impossible to saw them by eye: 0,5x2 micrometers (**Fig. 4**). But system had one disadvantage. It is required computer. That is why the sizes of information storage system were very and very big.

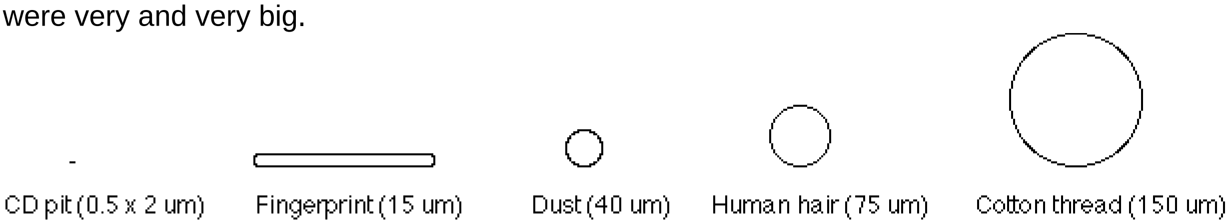


Figure 4

Simplest system for reading of the optical information is shown at **Fig. 5**. Such system consists of gas laser (at these years laser was a long tube with specially prepared gas); mirror; focusing objective which is condensing light energy to a small reading spot at information layer; glass disk with a thin metal foil on which information is coded; reading objective and photodetector. But this system also had a lot of disadvantages:

- very and very big sizes (laser, power sources for laser, computer for decoding an information signal;
- small reproducing speed because of inertia of relatively heavy objective;
- dust, scratches and fingerprints could easily distort information surface.

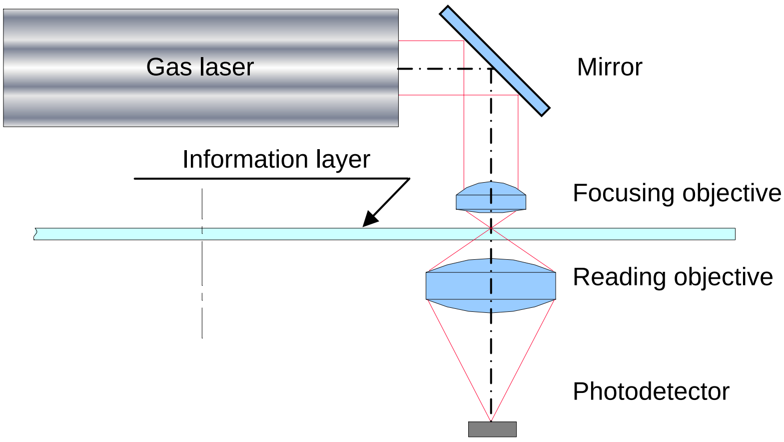


Figure 5

A year-by-year computer size has decreased very fast. Soon optical system only had limited total system sizes. So the next step of the recording system development is clear – to make it smaller. Take a look at **Fig. 5**. As you can see size problem appears particularly because of double-sides access to the disk.

Lets make simplest functional analysis for this system. Gas laser is generating light that is reflecting by mirror and focusing by objective at information layer. After that information modulated light goes through reading objective and focusing at photodetector (PD).

What do we have from this analysis (see **Table 1**)? We have that two objectives have the same function: to focus light. It is clear that we could try to trim one of these objectives and transfer its function to another. Philips engineers realized the same idea. It is obvious that if we trim reading objective light must be focused to photodetector by focusing objective. Than it is necessary that light goes up after disk. It means that disk must reflect light. OK, this idea didn't cause any problems. And what to do with photodetector (**Fig. 6**)?

From one hand we can't locate photodetector exactly after focusing objective

Table 1. Functional analysis.

Element	Function
Gas laser	**To generate** light
Mirror	**To break** optical axis for 90°
Focusing objective	**To focus** light energy in a small spot at information layer
Disk	**To modulate** light by the information
Reading objective	**To focus** information modulated light at photodetector
Photodetector	**To transform** light signals into electrical signals

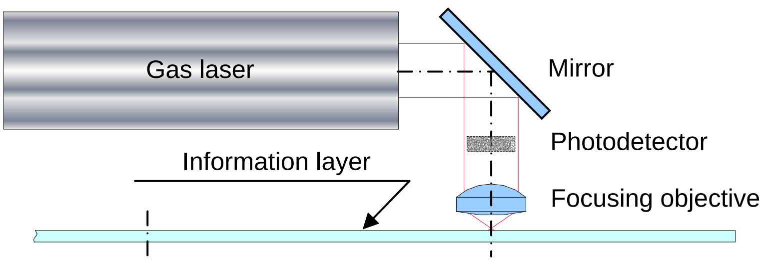


Figure 6

because we will shade laser beam before disk but from other hand when light will go back it will meet mirror and reflects back to the laser. Thus we've got physical contradiction: mirror must be to break optical axis for 90 degrees and mirror must not be to transmit light to photodetector. So we need to make such changes that could separate light which goes to disk and back.

So-called cubic beam splitter (CBS) could realize principle #3 *"Local quality"* (**Fig. 7**). But CBS has at least one disadvantage. It is not only reflects but also transmits light (50%-50%). It means that we will loose 50% on the way to disk and 50% when light will go back. Finally on PD we have not more then 25% of laser power (**Fig. 8**). Actually this does not matter because laser power could be easily increased. But the problem is in light, which goes back to laser. This light is breaking laser beam generation.

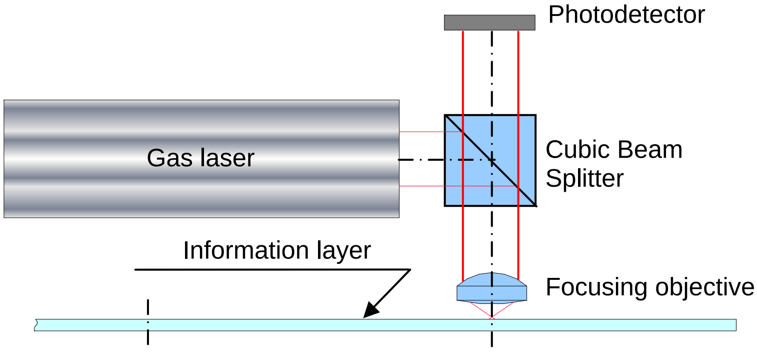


Figure 7

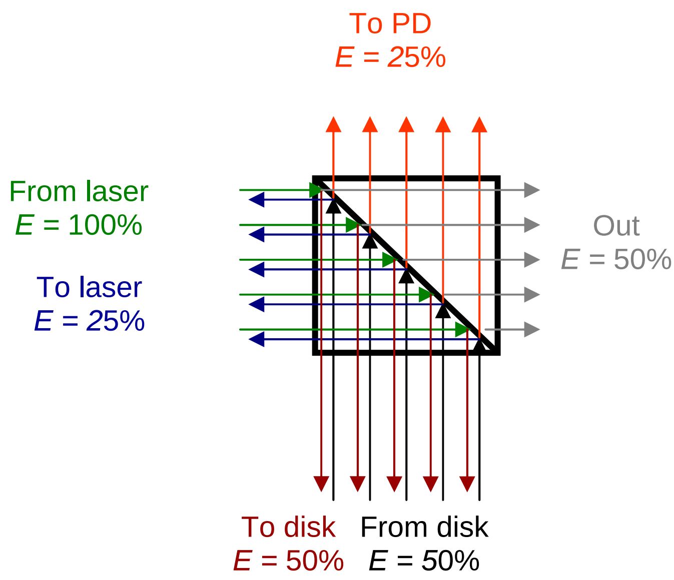


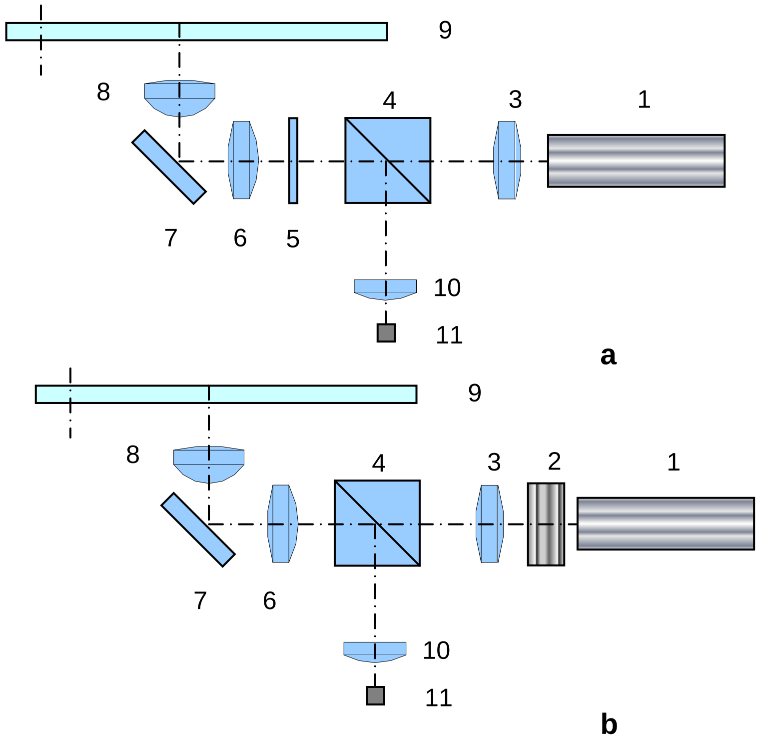
Figure 8

Generation must be stable but it can't be stable because of "back light". First of problem solving is to prevent light reflection. This is clear solution because we easily could find problem. To realize idea polarization properties of light were used (**Fig. 9a**). So-called quarter-wave plate 5 changes polarization state of light at its way to disk and on its way back. And then we can separate them by means of polarization coating at CBS 4.

The second solution is not clear.

Laser generation breaks just when "back light" is coming. But at microseconds or nanoseconds before light coming generation is OK. It is a mental inertia when we thing that light coming exactly at the same time. Light has final velocity and returns in very short time. So to prevent this problem it is necessary to divide time when laser could operate and could not operate. To realize this idea high frequency optical modulator 2 (**Fig. 9b**) was used.

At **Fig. 9** two solutions of this problem are shown. Finally manufacturers preferred the first solution because second one used very expensive optical modulator.



1. Gas laser
3. Focusing lens
4. Polarized Cube Beam Splitter
5. λ/4-Plate
6. Collimating Lens
7. Mirror
8. Objective Lens
9. Optical Disk
10. Sensor lens
11. PhotoDetector

1. Gas laser
2. Optical modulator
3. Focusing lens
4. Cube Beam Splitter
6. Collimating Lens
7. Mirror
8. Objective Lens
9. Optical Disk
10. Sensor lens
11. PhotoDetector

Figure 9

Here I wanted to put your attention that second solution was very unclear even for specialists. But with TRIZ we know that in accordance with principle #2 *"Separation"* contradictions could be divided not only in space (like in first solution) but also in time (like in second solution) as well. With this knowledge it is necessary just to check for possible resources.

The last problem that was described for system at **Fig. 5** is information layer pollutions. It is obvious that to prevent pollutions information layer should be covered by something transparent. Lets check what physical resources do we have at disk? Disk consists of metal foil (information layer) and glass substrate on which metal foil is sputtered. Main phrase here is *glass substrate*! We already have resource to prevent information layer of pollutions. Finally disk (Compact Disc standard) looks like it is shown at **Fig. 10**.

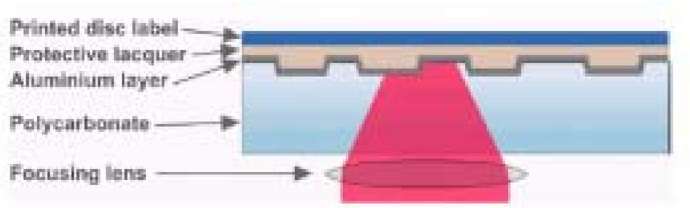


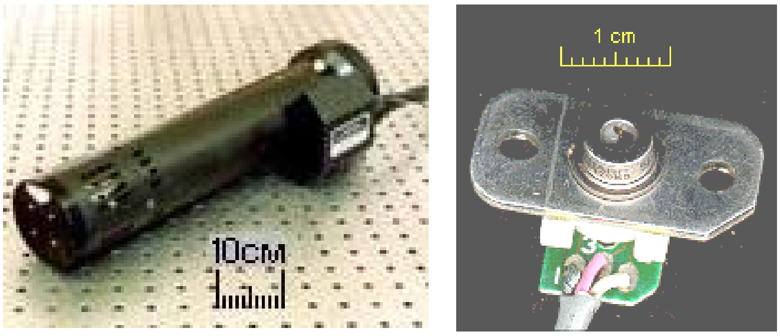
Figure 10

The main disadvantage of systems, which are shown at **Fig. 9** is laser sizes. To make new step it was necessary to make break through in laser designing.

In a middle of 1970th new laser was designed. This was tiny semiconductor laser (**Fig. 11**). And from that time sizes problem was finally resolved. System became such compact that could be placed into computer (**Fig. 12**).

However even this simple system has a number of disadvantages. First of them and much important is laser diode (LD) divergence. If after gas laser we have parallel light beam then after LD we have strongly divergent light (see **Fig. 13**). It does not cause any serious problem.

The second problem of Laser Diodes is that they make elliptical spot. This is not so important for reading systems and become very important for recording (**Fig. 14**). Usually system for recording information looks like it is shown at **Fig. 15**. As you can see there is one more extra-system to make spot after laser circular. And it is obvious that for recording systems we need to increase power. But as we saw before we have very big losses at CBS. That is why manufacturers combine both solutions, which were shown at **Fig. 9**. But instead of optical modulator 2 (**Fig. 9b**) electrical modulator of laser current was used.



Gas laser Semiconductor laser

Figure 11

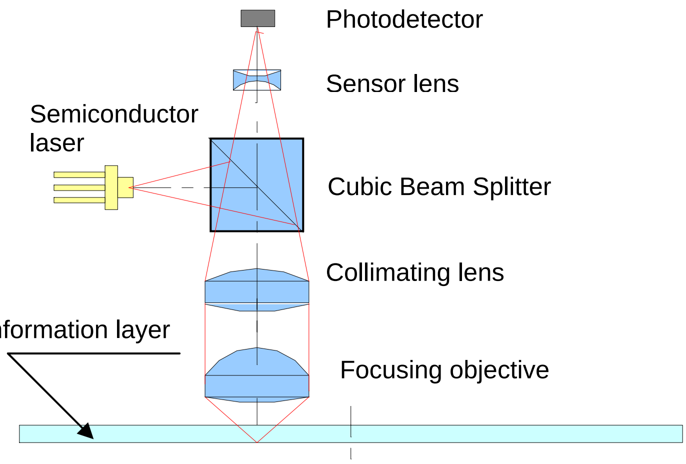


Figure 12

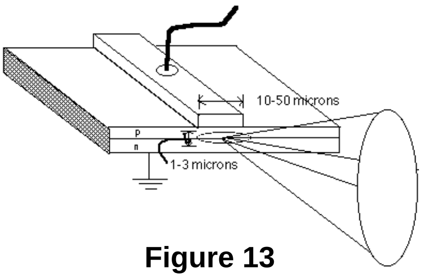


Figure 13

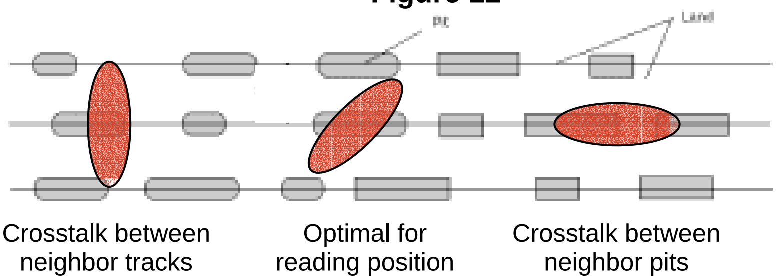
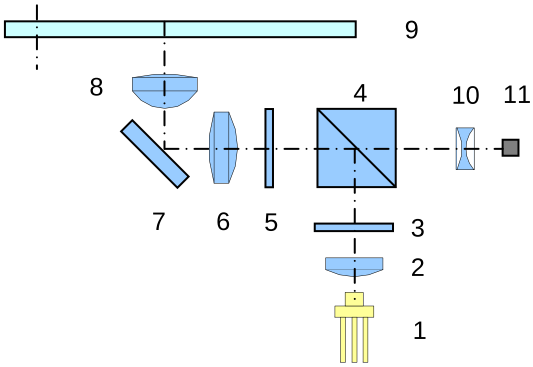


Figure 14

After these designs inventions in optical disk systems were practically stopped.

US patent for Compact Disc systems was valid just 17 years and had expired in 1999. Sony and Philips who have all rights for this patent decided to continue increasing of disks capacity. In 1996 it was suggested new standard of HD-CD (High-Density Compact Disc). Later it was renamed to DVD (Digital Video Disc). But now we know it as Digital Versatile Disc.

It was designed to keep movie with sound on 8 and subtitles on 30 languages. Disk consists of two bonded halves at inner side of which there are one or two information layers. It was suggested 4 types of DVD disks (see **Table 2**).



1. Laser Diode
2. Anamorphotic lens
3. Diffraction grating
4. Cube Beam Splitter
5. λ/4-Plate
6. Collimating Lens
7. Mirror
8. Objective Lens
9. Optical Disk
10. Astigmatic lens
11. PhotoDetector

Figure 15

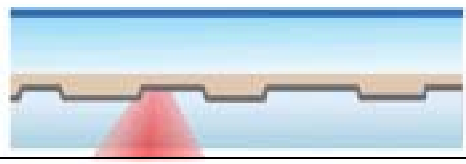
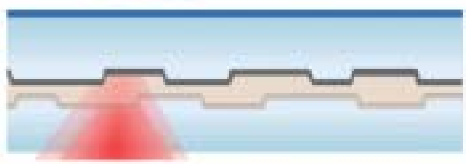
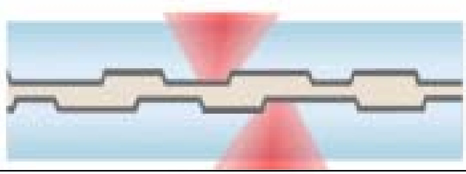
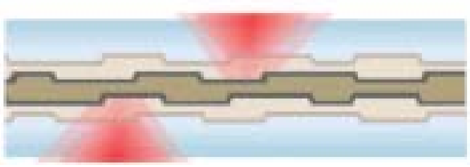
Increasing of the information capacity could be reached by decreasing of information marks on information surface (so-called pits). Physical limit of spot diameter 2ρ is described by approximation formula

$$2\rho = \frac{1{,}22 \cdot \lambda}{n \cdot \sin(\alpha)} \qquad (1)$$

where λ - laser wavelength; n - refractive index of the media; α - angle between marginal ray and optical axis ($NA = n \cdot \sin(\alpha)$ is the main parameter of any optical system so-called numerical aperture).

From formula (1) it is clear that to decrease spot diameter it is necessary to decrease λ or to increase NA.

Table 2. DVD disks types

DVD-5 discs comprise a sandwich of two 0.6mm substrates, one metallised and with data, the other blank, bonded together. Labels can be printed as for CDs.		4,7GB
DVD-9 discs comprise one semi-reflective substrate (layer 0) and one fully metallised substrate (layer 1) bonded together with an optically transparent layer. Labels can be printed on the discs as for CDs.		8,5GB
DVD-10 discs comprise two metallised substrates bonded together and read from both sides. The disc label is restricted to a small annular area within the disc hub, on both sides of the disc.		9,4 GB
DVD-18 discs, which have limited availability, comprise two dual-layer substrates bonded together and read from both sides. The disc label is restricted as for DVD-10.		17,0 GB

Designers decided to prefer perspective solution. At that time it already was technologically possible to make lenses with high numerical aperture $NA = 0{,}6$ (instead of 0,45 for CD) and lasers with smaller wavelength $\lambda = 655$ nm (instead of 788 nm). But both they were very expensive. Designers assumed that when systems will go to mass production the prices of lasers and lenses would be relatively small.

In principle it was not so difficult to make DVD system because of huge experience that was gathered during 17 years. But, as usual, it was one thing. In accordance with market rules it is necessary that consecutive system included the functions of preceding system. Or by other words DVD-Player must play all types of CD-disks, which were collected by customers.

It is necessary to explain before why DVD-disk could not be played by CD-device. From formula (1) it is clear that for concrete optical system with fix laser and fix objective lens we can't get different laser spot sizes. That is why we could not use DVD-disk in CD system. Spot size too large to read information (**Fig. 16**). And because spot too small we can't read CD-disk in DVD system.

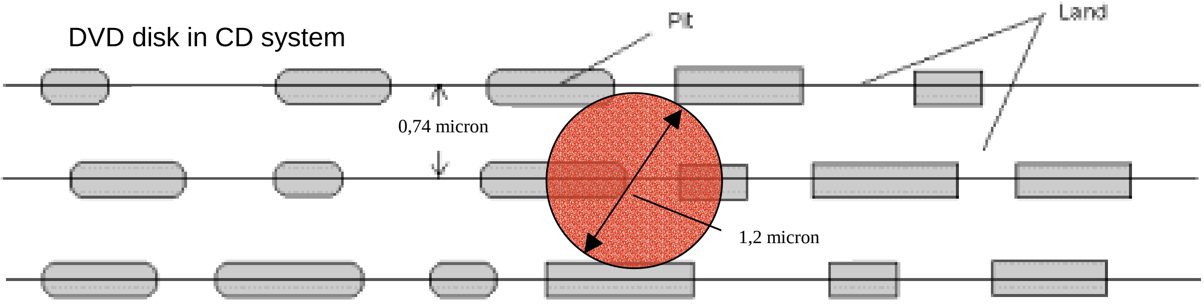


Figure 16

And the second reason is that we can't use DVD laser to read CD-recordable (CD-R and CD-RW) disks because of absorption of DVD-wavelength by recordable layer.

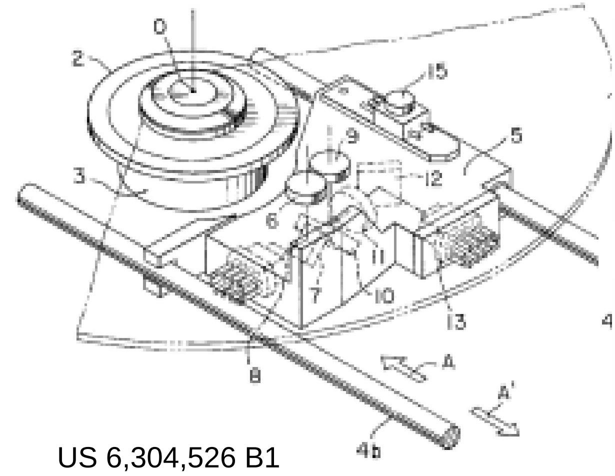
That is why these two things caused an explosion of inventions in this field.

As we already understood there are only one-way to reach full compatibility of both CD and DVD disks families: to use two lasers and two objectives. Or by other words we need to include full CD system in DVD. Some designers went by this way. At **Fig. 17** it is shown pick-up with two lasers (8, 13) and two objective lenses (6,9). At **Fig. 18** it is shown double pick-ups design (4, 5). But these are very and very expensive solutions. So it was necessary to search for other ideas.

It is clear that we can't use just one laser for this system. Then we can stop thinking about this. The second is that it is possible to make double objective lens pick-up. This will be our prototype for the next step. Next step here is trimming. It is necessary to remove from this prototype all elements with duplicate functions. Here there are two objective lenses (6 and 9) two mirrors (7 and 10) and two electromagnetic tracking systems (are not shown). And if we can trim one of objective lens we also easily remove from system mirror and controlling system. How to remove one of objective lens?

Lets discuss more detail what does numerical aperture mean. As you can see from **Fig. 19** for fixed f' and D values $NA = n \cdot \sin(\alpha)$ and can't be changed. So to change numerical aperture it is necessary to change f', D or both. Thus it seems to be that one lens could not

US 6,175,545 B1



US 6,304,526 B1

Figure 17

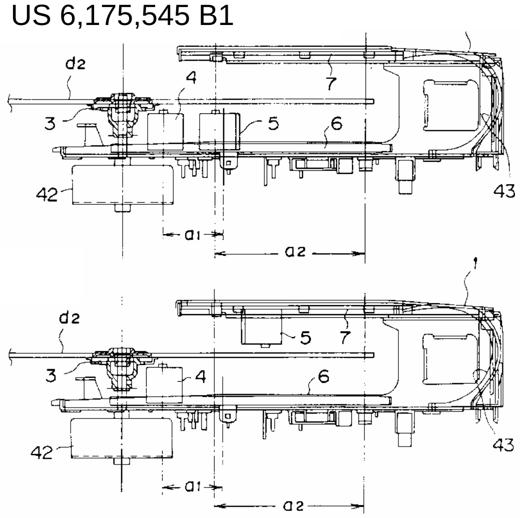


Figure 18

be used in CD/DVD pick-up. But take a look at **Fig. 20**. There are shown two possible cases of two-lenses pick-ups with on fix parameter. From optical systems design it is well known that it is impossible to realize first variant that shown at **Fig. 20a**. To realize idea that is shown at **Fig. 20b** it is necessary to have diaphragm. In depends on which laser do you use it will change diameter D that will change numerical aperture NA. There are a lot of variants how to use this method:

1. mechanical diaphragm (**Fig. 21**);
2. liquid crystal display (LCD) diaphragm (**Fig. 22**);
3. optical filtering (**Fig. 23**). Here DVD wavelength transmits, CD – scatters (the same idea with LCD).
4. other “exotic” methods (**Fig. 24**). Here beam diameter decreases by mirror that is could change its curvature.

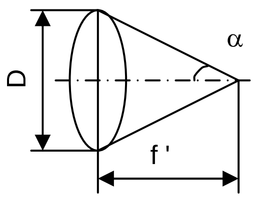
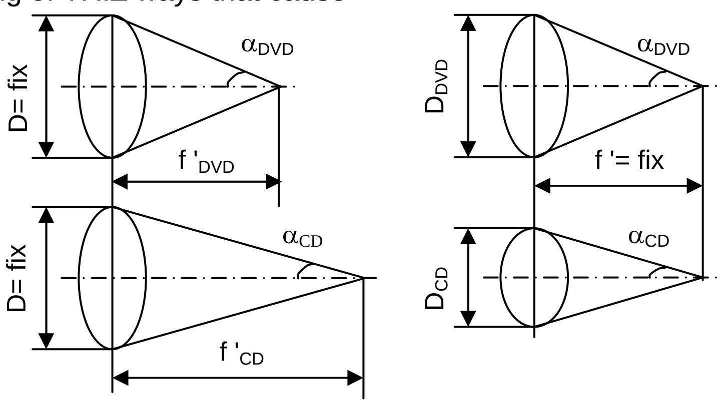


Figure 19

But as you know from the beginning of TRIZ ways that cause new element introducing are not cheap. The same situation is here. Systems became very expansive.

As you can see from **Fig. 23** optical filter consists of two parts: inner part for both CD and DVD light and outer part is for DVD only. But this solution suggests inserting of new element in the system. And by the way experiments showed that this element is very critical for adjustments. So we also will loose quality.

What do we have from resources? There are just 3



a **b**

Figure 20

elements that could be used to functions transferring: CBS, CL and OL (see, for example, **Fig. 22** and **23**). But because of long distance we can use neither CBS nor CL. Then we have just one resource – Objective Lens. So to trim optical filter it is necessary that OL will provide optical filtering features.

I want to pay attention to such long thinking process. If you missed one of these steps it is practically impossible to find easiest in realization solution. But in accordance with TRIZ this solution was very clear*:* principle #1 *"Segmentation"* and #3 *"Local Quality"*. These are two principles that were used here.

And again after that time there were an explosion of inventions about objective lenses with optical filtering function. For example at **Fig. 27** there are

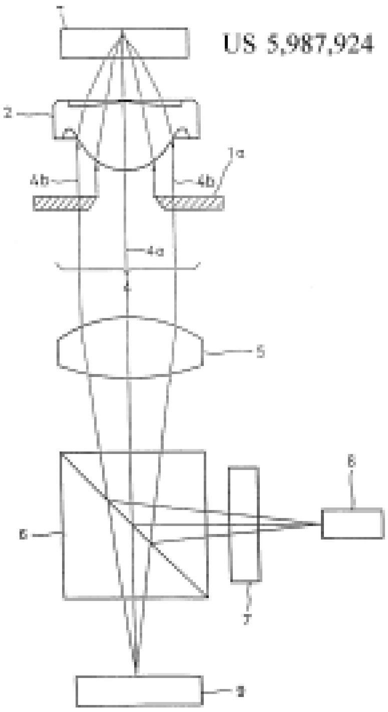


Figure 21

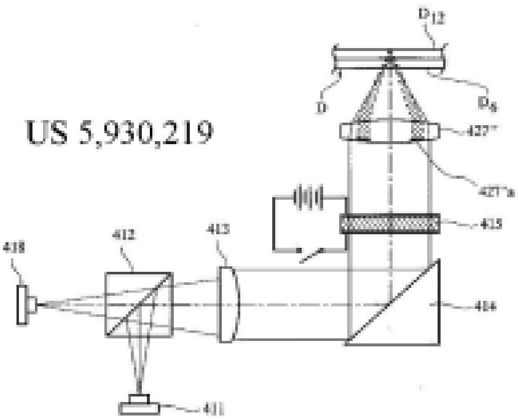
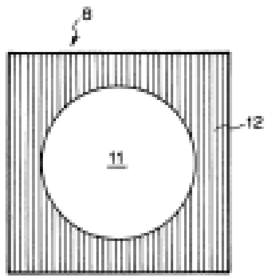


Figure 22



US 6,094,308

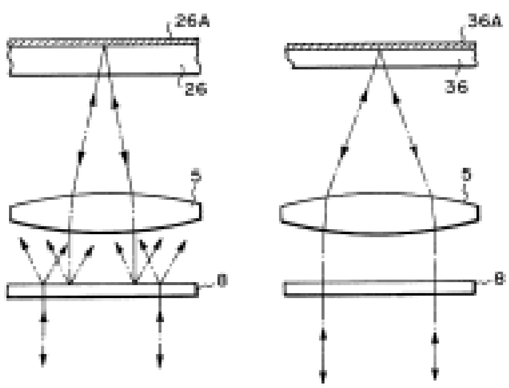


Figure 23

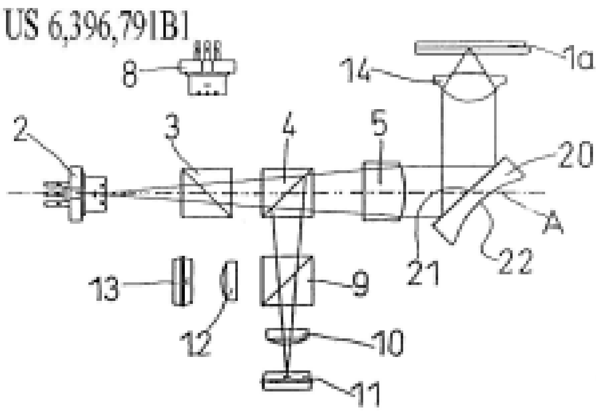


Figure 24

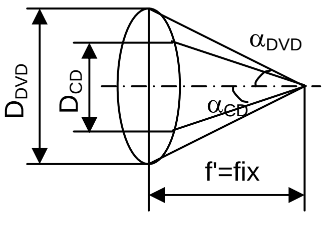
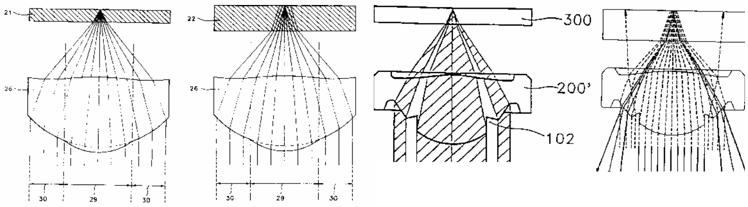


Figure 25

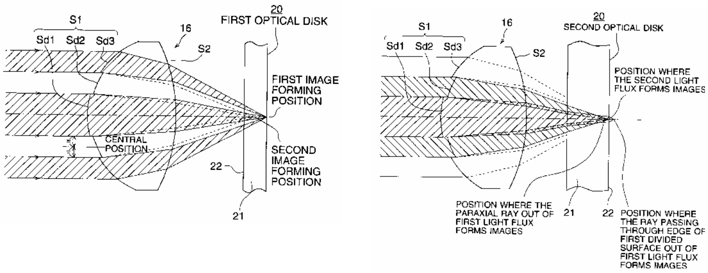
shown two types of lenses with an optical filtering (US 5,703,862 and US 5,870,369). **Fig. 28** is shown how does such lens operate (US 6,313,956). At **Fig. 29** it is shown very interesting lens (US 6,118,594). Here both used principles are very clear.

All the materials that I've presented above were historical



a b

Figure 27



a b

Figure 28

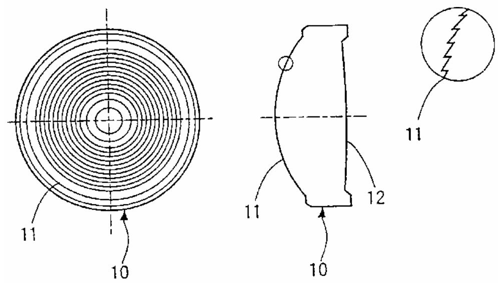
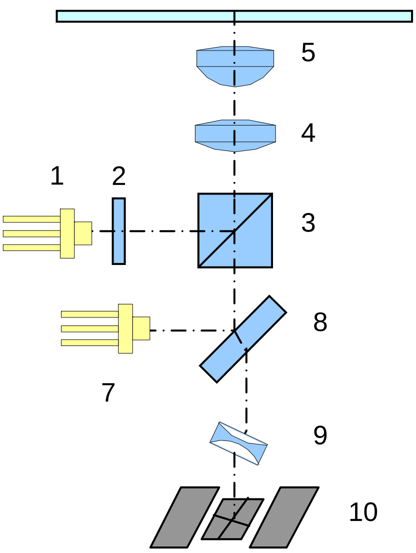


Figure 29

review. Finally after this review we could say that if designers would use TRIZ-technology designing time will be highly decreased.

And now I want to present trend designing that I made.

As a prototype for our trend we take classical optical system (**Fig. 30**). First step of any trend designing is functional analysis (**Table 3**).



Classical optical Pick-up scheme (prototype)

1. CD Laser Diode (CD LD)
2. Grating structure (GT)
3. Cube Beam Splitter (CBS)
4. Collimate Lens (CL)
5. Objective Lens (OL)
6. Disk
7. DVD Laser Diode (DVD LD)
8. DVD Half-Mirror
9. Sensor Lens (SL)
10. PhotoDetectors (PD)

Figure 30

Table 3. Functional analysis

Position	Element	Useful function	Harmful function
1, 7	Laser Diode	Laser light generation	Different radiance angles in two orthogonal directions cause neighbor tracks and pits crosstalking noise
2	Grating structure	Divide light beam onto three for tracking	Main beam intensity decreasing
3	Cube Beam Splitter	Optical axis breaking	Light loosing
4	Collimating Lens	Collimate laser light in objective lens direction and focusing in photodetector's direction.	Passive element that transmits wavefront distortions in both directions: to disk and to photodetector.
5	Objective Lens	Objective lens focuses light energy onto information layers of two different disk types.	Objective lens consists of three zones. During reading information at least one zone produces noise.
6	Optical Disk	Substrate protects information of fingerprints, scratches.	Substrate contains a lot of defects (such as black spots, air bubbles and pits missing) that corrupt information.
8	DVD Half-Mirror	Optical axis breaking; astigmatism introducing.	Light loosing; flat half-mirror introduce coma in system.
9	Sensor Lens	Coma compensation; spot size correction	Passive element: transmit noises to photodetector.
10	Photodetector	Transformation of light signal into electrical; signals amplifying	Passive element: noises also amplifies

First of all it is necessary to make system cheaper but with the same or better quality. Much expansive optical element here is CBS. From **Table 3** it is clear that we have two elements with the same useful function CBS (3) and DVD HM (8). To make system cheaper it is necessary to change CBS by HM and also eliminate harmful function. To make this operation here could be used such principles as #22 "*Blessing in disguise*" and #9 "*Preliminary counteraction*". We can eliminate Laser astigmatism by HM astigmatism (**Fig. 31**).

The next possible step is to trim sensor lens. Without Sensor Lens spot at photodetector became too small. But here we could use principle #22 "*Blessing in disguise*" and principle #13 "*The other way around*". Why do we tend to remove coma from optical system (see Table 3)? Lets increase coma to provide spot size correction (**Fig. 32**). So we transfer spot correction function to HM (which is became thicker) by increasing of coma.

If somebody needs in perfect circular shape on PD then after searching for useful resources we can suggest idea that is shown at **Fig. 33**. Here functions of Sensor Lens were transferred carefully.

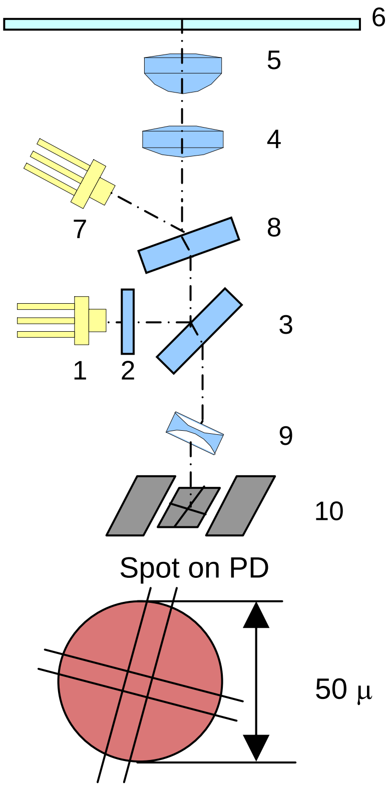


Figure 31

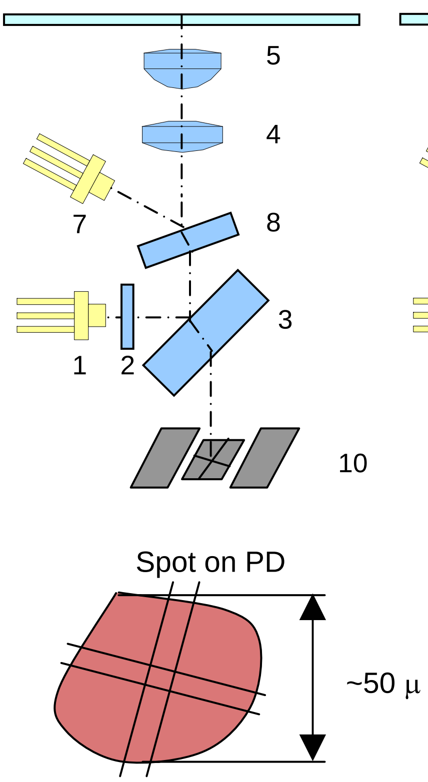


Figure 32

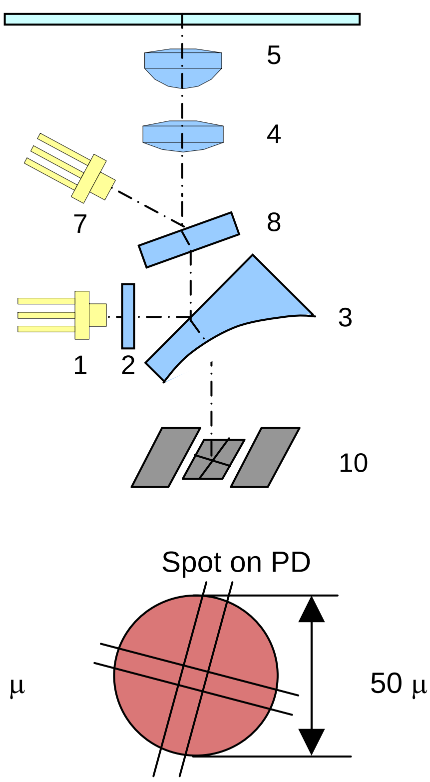


Figure 33

As we can see from the all our new designing there are two half-mirrors with the same functions. How to remove one of them?

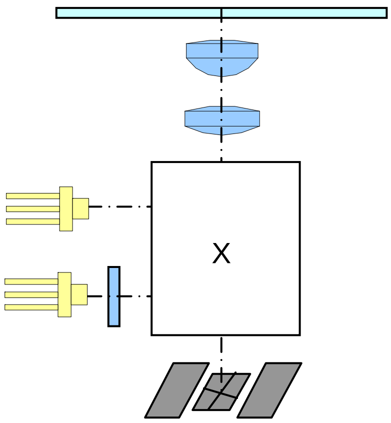


Figure 34

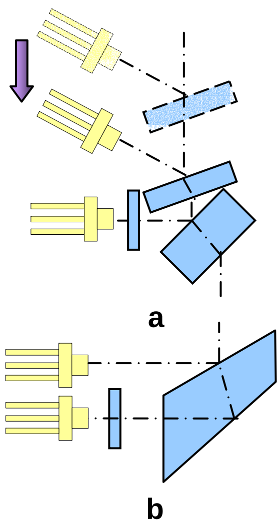


Figure 35

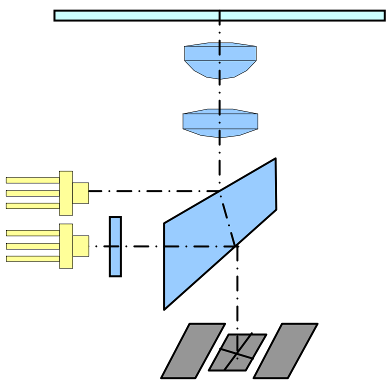


Figure 36

Lets change both these half-mirrors by **X**-element (**Fig. 34**). So this **X**-element must reflect laser light from both lasers. How to do it? Take a look at **Fig. 35a**. What will happen if we will decrease distance between two lasers? Distance could decreases until half-mirrors touch each other. And when they touch each other an idea appears: to make element that is shown at **Fig. 35b**. Finally system looks like it is shown at **Fig. 36**.

And what will happen if we continue decreasing distance between two lasers? In this virtual situation prism will not be necessary because distance will be very small.

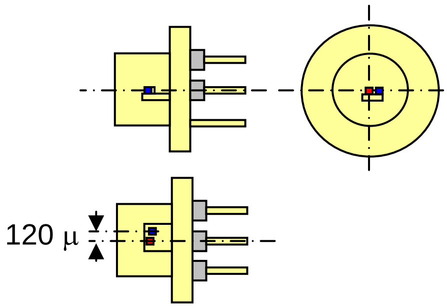


Figure 37

But this "virtual" situation became reality 3 years ago when first twin-laser was produced (**Fig. 37**).

Simplest optical layout with this twin-LD is shown at **Fig. 38**. But this layout is enough problematic. Yes, we improve system. But as you can see laser 1 is out of axis. Optical system is very sensitive for all asymmetries. Moreover with such laser we can't locate both laser spots at on photodetector. Lets draw all possible variants of such system correction. There are two ways when we can make one optical axis: before disk and after disk. To do this it is necessary to insert to system new Hologram Optical Element 10 (**Fig. 39** and **40**). The next way is to make one optical axis by means of principle

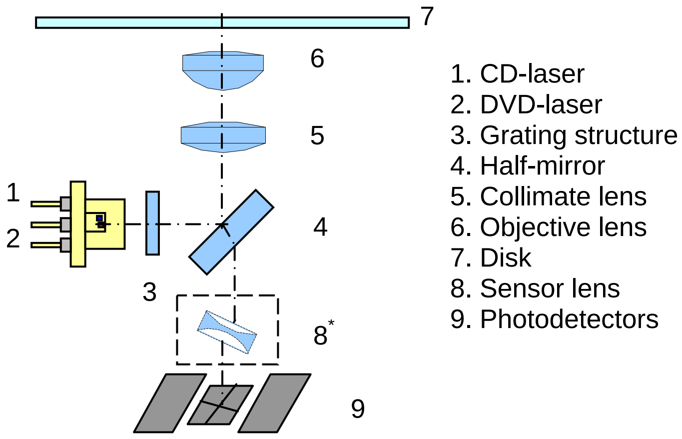


Figure 38

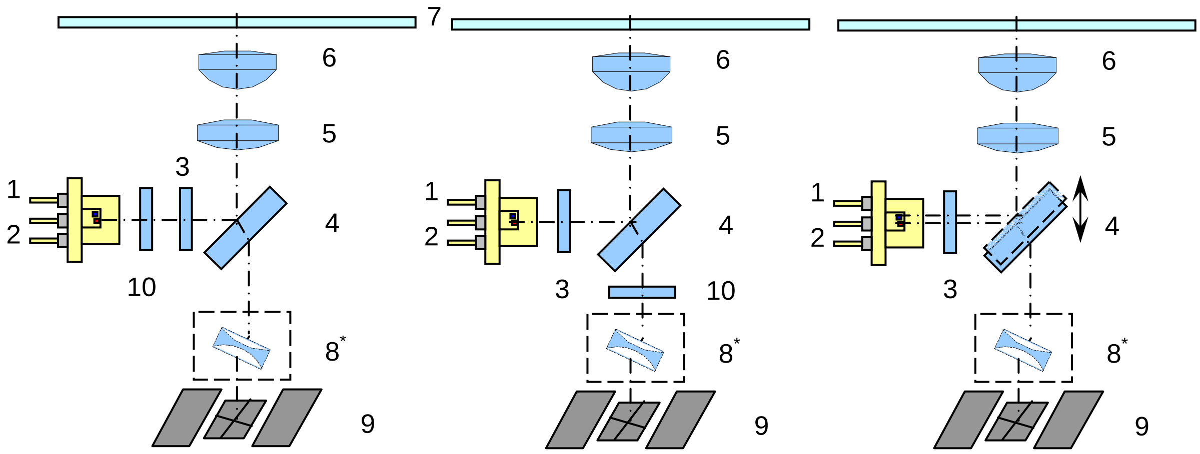


Figure 39 **Figure 40** **Figure 41**

#15 *"Dynamic parts"* (**Fig. 41**). Mechanical system moves HM when it is necessary to switch between lasers.

We can also remind system that is shown at **Fig. 36** and suggest the next system (**Fig. 42**). By the way why do we try to put both laser spots at one photodetector? What about "*Blessing in disguise*"? Lets make second photodetector where second light spot is focused (**Fig. 43**).

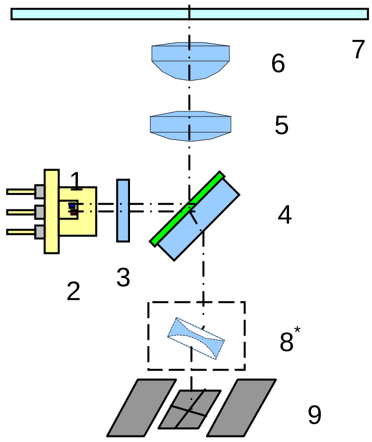


Figure 42

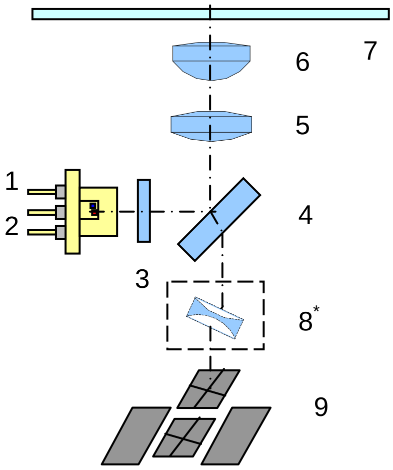


Figure 43

As you can understand we can easily remove sensor lens 8 from all layouts **Fig. 39-43**.

I suppose that next step in evolution will be trimming of Collimator Lens 5. We can do this step by two ways:

- transfer functions of CL to Objective Lens (**Fig. 44)**;
- transfer functions of CL to Half-Mirror (**Fig. 45**).

This work is not pretend to be full description of thinking process. But these materials are shown up that TRIZ technology could highly improve designing work because it could predict further system developing. In accordance with TRIZ it is easy to say that future of optical reading and recording systems in optical layout like shown at **Fig. 46**.

How to do next step? Lets thing together.

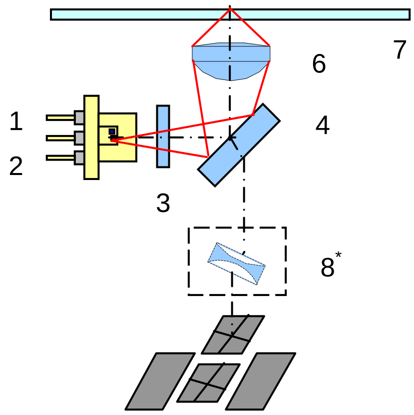


Figure 44

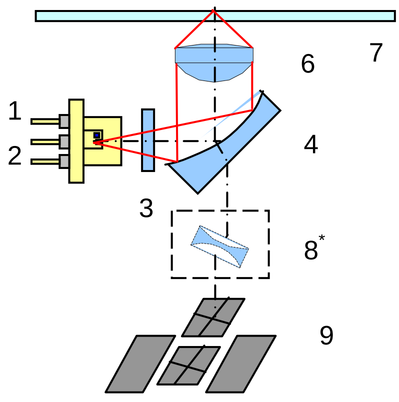
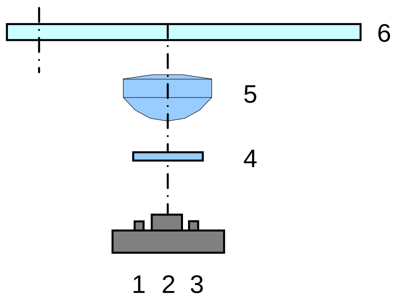


Figure 45



1. CD Laser Diode
2. PhotoDetector
3. DVD Laser Diode
4. Hologram Optical Element
5. Objective Lens
6. Disk

Figure 46